A STUDY OF THE PHYSIOLOGIC DETERMINANTS OF AN OPTIMUM METHOD OF ENDOTRACHEAL ASPIRATION IN PATIENTS WITH ACUTE RESPIRATORY FAILURE

by

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ABSTRACT

Eight patients requiring ventilation for acute respiratory failure were studied to identify the physiological determinants of a clinically successful method of endotrachael aspiration in patients with acute respiratory failure by: (1) determination of the magnitude of changes of specific hemodynamic and respiratory variables which occur during and after endotracheal aspiration; (2) investigation of the correlation between the magnitude of hemodynamic and respiratory changes during endotracheal aspiration and their physiological status prior to aspiration; and (3) determination of whether a standardized length of preoxygenation time provides adequate safety during endotracheal aspiration or whether a clinical index, e.g., compliance, would serve as an appropriate guide to the length of preoxygenation time necessary to prevent hypoxemia.

A standardized suction sequence was used in which each subject received thirty seconds of hyperinflation with one hundred per cent oxygen through a volume-controlled ventilator prior to suction, a twenty second period of suction, and a thirty second period of hyperinflation with one hundred per cent oxygen before returning to baseline ventilation. In addition,

a five minute period of oxygen washin was performed on each subject approximately one hour prior to institution of the suction sequence.

Arterial oxygen tension (PaO_2) increased from 85 $\pm$ 13 (mean $\pm$ S.E.) from before institution of the suction sequence to 96 $\pm$ 14 (mean $\pm$ S.E.) after return to baseline ventilation. Alveolar-to-arterial oxygen tension difference ($A\text{-}aDO_2$) decreased from 191 $\pm$ 18 (mean $\pm$ S.E.) before suction to 183 $\pm$ 17 (mean $\pm$ S.E.) after suction. Since these subjects were apparently in a steady state during the measurements as evidenced by no change in the rate of CO_2 production, the standardized suction sequence in these subjects was adequate not only to prevent an overall decrease in arterial oxygen tension but to provide a net result of improved arterial oxygenation through decrease in the $A\text{-}aDO_2$.

Identification of a clinical measurement which would predict the change in PaO_2 during the suction sequence was made through correlating a wide range of hemodynamic and respiratory variables measured prior to the suction sequence to the per cent change in arterial oxygen tension during the suction sequence. That variable which was found to best predict the per cent change in arterial oxygen tension was the per cent of oxygen washin at the end of thirty seconds of hyperinflation with 100 per cent oxygen ($r = 0.799$; $p < 0.05$) and the rate of washin

(r = 0.719; $p < 0.05$). That other variables thought to affect the per cent change in arterial oxygen tension during the suction sequence were not significant predictors may be the result of the effectiveness of the hyperpreoxygenation before the actual period of aspiration.

Determination of whether a standardized length of preoxygenation time provides adequate safety during endotracheal aspiration or whether a clinical index, e.g., compliance, would serve as an appropriate guide to the length of preoxygenation time necessary to prevent hypoxia was made through examining the factors which affect the washin of oxygen. Oxygen washin occurs exponentially, and oxygen washin curves in the subjects studied demonstrated four phases: Phase I--the initial plateau; Phase II--the fast filling component; Phase III--the slow filling component; and Phase IV--the reabsorption component.

Since the standardized length of preoxygenation time occurred during Phases I and II, factors predicting the rate of washin of these phases were identified as the baseline fraction of inspired oxygen (FIO_2) (r = -0.803; $p < 0.05$), the $A\text{-}aDO_2$ (r = -0.964; $p < 0.05$), and the shunt fraction ($\dot{Q}_{VA}/\dot{Q}_T$) (r = -0.786; $p < 0.05$). $A\text{-}aDO_2$ was the single best predictor of the rate of washin of Phases I and II combined accounting for 72 per cent of the variance ($p = 0.016$) and of the rate of washin

of Phase II alone, accounting for 75 per cent of the variance ($p < 0.01$). The combined effects of $A\text{-}aDO_2$ and $\dot{Q}_{VA}/\dot{Q}_T$ were the best predictors of the rate of washin of Phases I & II, accounting for 86 per cent of the variance ($p < 0.02$), while $A\text{-}aDO_2$ and FIO_2 were the best predictors of the rate of washin of Phase II alone, accounting for 84 per cent of the variance ($p<0.025$). The deadspace ratio (V_D/V_T) was the best single predictor of the rate of washin of Phase III ($r = -0.848$; $p < 0.05$).

Thus, clinically the rate of washin of oxygen can be predicted in an individual patient through use of an easily measurable variable, the alveolar-to-arterial oxygen tension difference, and with even greater accuracy by using the shunt fraction ($\dot{Q}_{VA}/\dot{Q}_T$) in combination with the $A\text{-}aDO_2$. The clinician who must suction mechanically ventilated patients in whom arterial oxygen tension is low can predict that those subjects who have large $A\text{-}aDO_2$ and large $\dot{Q}_{VA}/\dot{Q}_T$ will need longer periods of hyperinflation with 100% oxygen in order to raise their arterial oxygen tensions to clinically acceptable levels prior to suction than those with low $A\text{-}aDO_2$ and $\dot{Q}_{VA}/\dot{Q}_T$.

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TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION AND PROBLEM DELINEATION

Endotracheal aspiration is a hazardous procedure which is performed frequently in the intensive care management of critically ill patients. When used in conjunction with mechanical ventilation, it is nevertheless an effective means of eliminating copious secretions in patients with acute respiratory failure. The purpose of this study is to explore the physiological determinants of a clinically successful method of endotracheal aspiration in patients with acute respiratory failure.

The following sequence of events, taken from the chart of a forty-nine year old male patient with blunt trauma (from falling several stories in height) illustrates the magnitude of the effect of the suctioning procedure on arterial oxygen tension in one patient:

> As noted, patient extubated self last night. It was decided to let him try to ventilate on his own with reintubation a definite possibility. His PaO_2[1] was only 52 this AM on nasal prongs. He was found with his face hood off. Repeat PaO_2 was 132

on nasal prongs and hood. Vital capacity 1300 cc.

To determine the effect on his PaO_2 of NT[2] suctioning, serial ABG's were drawn. Previous PaO_2 = 132, during suctioning = 98, immediately after about 5 seconds of suctioning = 80, and five minutes later = 100.

The nurses were impressed with the significance of these measurements, i.e., 52 mm drop in PaO_2 in only 5 seconds of suctioning.[4]

In addition to decreased arterial oxygen tension, which is exemplified above, endotracheal aspiration has been associated with a number of other complications, e.g., atelectasis, cardiovascular collapse, and even death. In patients with acute respiratory failure, the problem of the provision of adequate oxygenation may be of critical importance if respiration is compromised by suctioning.

Problem Delineation and Problem Statement

Problem Delineation

In 1970, Abdellah listed the maintenance of a supply of oxygen to all body cells as one of the areas on which nursing research should focus during the seventies. "Criterion measures of patient care and precise instrumentation to measure the effects of practice upon patient care" were identified as the major gaps

in nursing research (p. 15).

A survey of the nursing literature related to the process of endotracheal aspiration, however, yields no studies related to aspiration and only a few references to the "do's" and "don'ts" of the procedure. Beland (1970) and Secor (1969) mention the practice of hyperoxygenation prior to aspiration as advisable, but neither of these sources specifies the length of time nor the percentage of oxygen that should be used. Jacquette (1971) discusses preventing cardiac arrhythmias by the administration of one hundred per cent oxygen for five minutes prior to aspiration and for an unspecified period of time after aspiration, keeping the aspiration period brief (about 8-10 sec.), and reducing the negative pressure to the lowest level that will "do the job." Wade (1973) suggests a few breaths with one hundred per cent oxygen to prevent hypoxia in the already hypoxemic patient, limiting the aspiration period to fifteen seconds with adequate reoxygenation of the patient between times, and limiting the diameter of the suction catheter to no greater than half that of the main bronchi. Other sources (Brunner, Emerson, Ferguson, & Suddarth, 1970; Shafer, McCluskey, Beck, & Phipps, 1971) mention only the length of time that the suction should be applied.

In clinical practice, moreover, there is a diversity in the methods used for endotracheal aspiration both between institutions and between practitioners within institutions. For example,

in some institutions endotracheal aspiration is performed without the administration of any oxygen, while in others at least one minute of oxygen is given both before and after aspiration. Results of this study, therefore, can provide a theoretical basis for decision-making regarding the therapeutics of the apsiration procedure.

Problem Statement

What are the physiological determinants of a clinically successful method of endotracheal aspiration in patients with acute respiratory failure?

Objectives of the Study

The broad objectives of the study were as follows:

1. To determine the magnitude of changes of specific hemodynamic and respiratory variables which occur during and after endotracheal aspiration in patients with acute respiratory failure.

2. To investigate in patients with acute respiratory failure the correlation between the magnitude of hemodynamic and respiratory changes during endotracheal aspiration and their physiological status prior to aspiration.

3. To determine whether a standardized length of preoxygenation time provides adequate safety during tracheo-bronchial aspiration or whether a clinical index, e.g., compliance,

would serve as an appropriate guide to the length of preoxygenation time necessary to prevent hypoxemia.

Thus, results of this study contribute additional data about endotracheal aspiration which may lead to the early recognition of patients at hazard during the procedure. Studies in the past have focused on the degree of arterial oxygen desaturation during endotracheal aspiration and on the methods of oxygenation that could be used to prevent desaturation. No other study has examined the wide range of hemodynamic and respiratory variables included here.

CHAPTER II

RATIONALE

This investigation was divided into major components--first, a study of the physiological consequences of a standardized method of endotracheal aspiration in patients with acute respiratory failure, and second a study of the respiratory and mechanical factors which affect the washin of oxygen in patients with acute respiratory failure. The theoretical basis for the study was derived from theories of the physics of the process of suction as well as from research findings relating the physiological effects of changes in inspired oxygen concentration and atelectasis to specific respiratory and hemodynamic variables. This rationale has been divided into the following sections:

I. A theory of the mechanics of suction.

II. A theory of the effect of endotracheal suction on respiratory function.

III. Theories of the physiologic determinants of oxygen washin.

IV. Description of the pathophysiology of acute respiratory failure.

V. Description of relationships in steady-state gas exchange.

The Mechanics of Suction

Suction is the flow created by lowering the pressure at one end of a tube. Several factors influence the flow in smooth tubes. First, the flow is proportional to the pressure difference between the ends of the tube when the flow is laminar. When there is turbulence in the flow, the flow is proportional to the square root of the pressure difference between the ends of the tube. Thus, in turbulent flow it takes a greater increase of pressure to cause an increase in flow (Rosen & Hillard, 1960; West, 1974).

The second factor influencing flow in smooth tubes is resistance. In a suction catheter, the resistance depends on the diameter and length of the tube. In laminar flow, the viscosity of the fluid also affects the flow as does the density of the fluid in turbulent flow. The main factor, however, affecting the flow through the suction catheter is its diameter, as in the case of laminar flow it is directly proportional to the fourth power of the radius (Poiseuille's Law). Thus, in general, flow is increased by increasing the bore of the catheter (Rosen et al., 1960; West, 1974).

The pressure in one end of the suction catheter is lowered by a suction apparatus which produces a negative pressure thus overcoming the resistance of the catheter and inducing flow. There are several different types of suction apparatuses, and the

characteristic manner in which flow is induced is peculiar to each type. In general, the greater the negative pressure developed by the apparatus, the greater will be the flow through the catheter.

Initially, when negative pressure is applied to the catheter, air alone flows through the circuit. When the tip of the catheter is placed in liquid, e.g., mucus, the flow of air decreases, negative pressure develops, and the flow of liquid increases to a level determined by the pressure and flow characteristics of the suction apparatus and the physical characteristics of the liquid.

The volume of liquid removed is determined by the average pressure in the system during the period of suction. The more rapid the increase in negative pressure, the greater is the volume of liquid removed. The time that the negative pressure takes to develop depends on the volume of air in the system, the rate at which it is removed, and the maximum negative pressure that the apparatus can produce. Since the circuit is evacuated against a continually increasing negative pressure so that the rate of increase of negative pressure gradually becomes slower and slower, the rate of increase is exponential in nature, i.e., as the negative pressure develops, the flow decreases and the rate of increase of negative pressure becomes gradually slower.

There are a number of sources by which negative pressure can be produced--pumps, injectors, and gravity. Pump sources, which are the type generally used for endotracheal aspiration,

have a suction cycle followed by a discharge cycle. The type of pump--rotary, piston, or diaphragm--determines whether the action depends on valves or whether valves are not needed. A power source is required for each type. Pipeline suction is an extension of the suction provided by an electric pump, usually of the rotary type. A large tank acts as a reservoir of negative pressure and is fitted with maximum and minimum pressure switches. When the negative pressure is lowered to one limit, the motor is activated and then deactivated when it has reached the maximum pre-set limit. Along the pipeline, the size of each intake is restricted so that no one intake allows flow to reach the maximum which the pump is capable of producing. Flow at each intake is regulated by controls at that intake (Rosen et al., 1960).

A Theory of the Effect of Suction on Respiratory Function

Endotracheal aspiration is a common procedure used to remove bronchial secretions in patients with indwelling endotracheal tubes. When the suction catheter is passed down the endotracheal tube and negative pressure applied, air flows from the atmosphere into the tracheobronchial tree and up the catheter into the suction apparatus. There is a fall in pressure from the atmosphere to the airway and again from the airway to the suction apparatus. This pressure drop is

proportional to the resistance of the pathway from the atmosphere to the airway. If the resistance of the pathway from the catheter tip to the atmosphere is high, a great portion of the negative pressure developed by the apparatus will also be developed in the airway. A decrease in transpulmonary pressure, a reduction in lung volume distal to the bronchi, and the possibility of atelectasis results. If the suction catheter stimulates the muscles of expiration, transpulmonary pressure could be further decreased and the pressure gradient might be reversed. As soon as solid or liquid aspirate is drawn into the suction catheter, the pressure in the airway once again becomes atmospheric (Rosen & Hillard, 1962).

Conditions under which decreases in transpulmonary pressure are likely to develop can be determined. Since the pressure drop along a tube is equal to the product of its resistance and the flow along it, when an equilibrium is reached air flows down the trachea at the same rate as it flows up through the catheter. Thus, the ratio of the outside diameter of the suction catheter to the inside diameter of the endotracheal tube through which it is passed is an important factor in determining the resistance of the pathway from the tip of the catheter to the atmosphere (Rosen et al., 1962).

Even subatmospheric airway pressures of brief duration, such as those produced by suctioning with a large suction catheter through a narrow endotracheal tube, can cause a decrease in

compliance and shunting (Rattenborg & Holaday, 1967). The mechanism responsible for this decrease in compliance is probably collapse of the alveoli (Egbert, Laver, & Bendixen, 1963). If the capillary blood flow is maintained through the collapsed, and thus unventilated, areas of the lungs, venous admixture to arterialized blood will occur. If enough alveoli collapse, but continue to be perfused, the venous admixture, or shunt, will assume such proportions that a measurable fall in arterial oxygen tension will result (Bendixen, Hedley-Whyte, & Laver, 1963). Collapse of the alveoli can also cause a decrease in functional residual capacity (Saklad & Paliotta, 1967).

Patients with respiratory failure generally have low resting lung volumes due to a variety of mechanisms, such as, atelectasis from airway obstruction by secretions. If these secretions are removed by suction and the lungs hyperinflated, an improvement in resting lung volume may result. This increase in FRC, if it is due to the opening of previously non-ventilated alveoli, may be accompanied by an improvement in compliance and shunt.

Decreased arterial oxygen tension has been reported during and after endotracheal aspiration in a wide variety of subjects. A number of mechanisms may be responsible: first, dilution of the alveolar gas with air in instances where the inspired oxygen tension is greater than room air; second, apnea in patients requiring

constant artificial ventilation; and third, atelectasis resulting from the development of intra-airway negative pressures with an accompanying increase in shunt and alveolar-to-arterial oxygen difference. It is possible that any or all three of these mechanisms may be operant in any one patient.

The amount of arterial oxygen desaturation which occurs during and after endotracheal aspiration may be related also to the degree to which any one of these factors is operant in an individual patient. A patient requiring a high inspired oxygen tension in order to maintain a clinically acceptable level of arterial oxygen tension might have a greater decrease in arterial oxygen tension from endotracheal aspiration than one being ventilated on room air, because of the dilution of alveolar gas with room air. Patients with low initial resting lung volumes and therefore with smaller amounts of alveolar gas might desaturate more quickly from aspiration and its accompanying apnea than those with large initial resting lung volumes. Finally, increased shunt which accompanies atelectasis may be responsible for decreased oxygen tension.

The common practice of endotracheal aspiration in intensive care, however, frequently includes hyperoxygenation and hyperinflation prior to and after aspiration. The rationale for this practice is to increase the volume of oxygen in the lungs prior

to aspiration as a prophylaxis against hypoxemia and after aspiration to reverse its untoward effects. The degree to which the factors responsible for decreased arterial oxygen tension are affected by this process is not certain.

Hemodynamic effects of endotracheal aspiration may be related to two factors: first, arterial oxygen desaturation which is responsible for a decreased supply of oxygen to the cardiac muscle and thus increased cardiac irritability, resulting in cardiac arrhythmias, and, second, increased venous return to the heart and its resultant effect on cardiac output. Under steady-state condition, any factor which affects venous return will also affect cardiac output (Guyton, Jones, & Coleman, 1973). If the veins leading to the heart are suddenly compressed, as could occur during the development of high positive intra-thoracic pressures during "bucking" (coughing against the endotracheal tube), while blood continues to be pumped out of the cardiac chambers and lungs into the aorta, a few beats could occur with little blood flowing into the right atrium. Conversely, cessation of this positive intra-thoracic pressure may cause increased cardiac output resulting from the emptying of the blood stored in the great veins during the low flow period. A heart with poor reserve might be unable to compensate for these sudden changes in cardiac output (Rosen et al,. 1962).

Theories of the Physiological Determinants of Oxygen Washin

Since hyperoxygenation prior to suction is used to prevent the untoward consequences of that procedure, it is clinically practical to know an optimum hyperpreoxygenation time. Using 100% oxygen it is possible to determine the amount of time necessary to reach the maximum arterial oxygen tension with 100% oxygen washin, i.e., his oxygen washin time. How rapidly and to what degree the arterial blood responds to change in the inspired oxygen concentration is dependant upon several factors: (1) alveolar ventilation and FRC (Eger, 1974); (2) the distribution of inspired oxygen (Colgan & Mahoney, 1969); (3) diffusion across the alveolar-capillary membrane (Staub, 1963); (4) the distribution of the pulmonary blood flow (Finley, 1961); and (5) the cardiac output (Briscoe, Cree, Filler, Houssay, & Cournand, 1960).

Alveolar ventilation. With a constant inspired concentration of oxygen (100%), the rate of rise of the alveolar concentration of oxygen is governed by the alveolar ventilation. The greater the ventilation the more rapid the approach of the alveolar to the inspired concentration. The functional residual capacity, however, limits the effect of the alveolar ventilation in that the larger the FRC, the slower the washin of oxygen and vice versa. The size of the tidal volume is of relatively little importance (Egar, 1974).

Distribution. Since pulmonary capillary blood can take up oxygen only to the extent that the concentration is presented to the alveoli, the speed and equality of the distribution of the inspired gas affects the alveolar-blood gas exchange. Even in the normal lung, all regions do not have the same ventilation. The lower regions of the lung ventilate better than the upper zones (West, 1974). In various postures, except at lung volumes lower than the functional residual capacity, pulmonary ventilation and perfusion are greater in dependent than in the upper zones of the lung, indicating that the distribution of both ventilation and perfusion is gravity dependent (Kaneko, Milic-Emili, Dolovich, Dawson, & Bates, 1966). In the normal lung artificial ventilation causes no detectable change in the uniformity of this distribution of inspired gas (Bergman, 1963; Hulands, Greene, Iliff, & Nunn, 1970).

In addition, airway closure affects the regional pattern of gas distribution and results in ventilation-perfusion inequality and impaired blood gas exchange. In the normal person, regardless of age, all regions of the lung are open at the end of a full inspiration. As the lung volume decreases during expiration, small airways show a progressive tendency to close, whereas larger airways remain patent. The lung volume at which appreciable small airway closure begins is the closing volume. With advancing age

there is an increased tendency toward airway closure and an increase in the closing volume (Mansell, Bryan, & Levinson, 1971).

Diffusion. Diffusion capacity is altered by two factors--the distance for diffusion and the surface area for diffusion. Normally, the path for diffusion is short, i.e., traversing a surface film covering the alveolar lining of the alveolar membrane, the interstitial fluid, and the capillary endothelium. In disease this pathway may be much longer if: (1) the alveolar wall is thickened; (2) the capillary membrane is thickened; (3) the two membranes are separated by interstitial edema fluid and exudate, which may be replaced by fibrous tissue; (4) there is intra-alveolar edema fluid or exudate; and (5) the intracapillary path is increased because the capillaries are dilated and contain several red blood cells abreast (Comroe, Forster, Dubois, Briscoe, & Carlsen, 1962.)

The surface area for diffusion can be decreased by any decrease in the number of patent capillaries or in the number of ventilated alveoli. Thus, the surface area can be decreased by diseases which disrupt normal alveolar architecture, by diseases which decrease functioning pulmonary capillary bed, or by diseases which cause significant block of airways and thereby decrease the number of alveoli available for gas exchange (Comroe et al., 1962).

Diffusion is also dependent upon the difference in alveolar-arterial gas concentration. In normal conditions the oxygen tension of the red blood cell as it enters the capillary is already about four-tenths of the alveolar value because of the oxygen in the mixed venous blood. Under typical resting conditions, the capillary oxygen tension reaches that of the alveolar gas when the red cell is about one-third of the way along the capillary (West, 1974).

Perfusion. Blood flow is not equal throughout the normal human lung. In the upright human lung, blood flow decreases almost linearly from bottom to top, reaching very low values at the apex. This distribution is affected by change of posture and exercise. When the subject lies supine, the apical zone blood flow increases but the basal zone flow remains virtually unchanged, with the result that the distribution from apex to base becomes almost uniform. In this position, blood flow in the posterior regions of the lung exceeds flow in the anterior parts (West, 1974).

In subjects in whom there is impairment of gas exchange in the lungs, there is wasted pulmonary blood flow or right-to-left shunt. A true shunt contains components from right-to-left intracardiac shunts, bronchial veins, and alveoli which are perfused but not ventilated. In healthy individuals at rest, the total shunt amounts to less than five per cent of the total cardiac output (Bates, Macklem, & Christie, 1971).

Oxygenation of the blood is retarded in proportion to the magnitude of the intrapulmonary shunting, since mixed venous blood passing through the shunt continually contaminates the arterial blood. The relative distribution of pulmonary blood flow to ventilated and to unventilated areas of the lung also affects the rate and degree of arterialization of the blood. Perfusion of unventilated areas of the lung probably accounts for most of the decrease in arterialization of the blood (Colgan & Fanning, 1970).

Cardiac output. Since the blood carries the gas away from the lungs, the greater the cardiac output, the greater the uptake of gas from the lungs (Egar, 1974).

Description of the Relationships in Steady-State Gas Exchange

The typical adult man at rest in the sitting position consumes about 300 ml oxygen and produces about 250 ml of carbon dioxide per minute. This gas is exchanged with the environment through the lungs, skin, and the urine and other secretions with the primary mode of exchange being the lungs.

The content of the inspired gas is nitrogen, oxygen, carbon dioxide, water vapor, and traces of other gases. Only the amount of water vapor is widely variable so that the fractional composition of the oxygen, nitrogen, and carbon dioxide are relatively constant and generally expressed in terms of the dry gas.

In the steady state, there is no net exchange of nitrogen with the environment, because this gas is neither produced nor consumed by the body. Since in the alveoli oxygen diffuses into and carbon dioxide out of the blood flowing through the pulmonary capillaries, the expired gas usually contains less oxygen and more carbon dioxide than the inspired gas. In addition, since as the inspired gas passes through the upper respiratory tract it becomes warmed to the temperature of the body and saturated with water vapor at this temperature, the expired gas also contains more heat and more water vapor than the inspired gas (Otis, 1964).

Pulmonary ventilation and gas exchange. Ventilation, the mass movement of gas in and out of the lungs, may be defined as either the volume expired or the volume inspired per minute. These two volumes, however, are not generally identical even in the steady-state. This inequality is due to the ratio of carbon dioxide production to oxygen consumption, the respiratory exchange ratio. Since in the steady-state the body neither produces nor consumes nitrogen, the rate of exchange of nitrogen is zero (Otis, 1964). The respiratory exchange ratio is generally accepted to be 0.8 in steady-state conditions (Nunn, 1969).

Alveolar ventilation and gas exchange. At the end of each inspiration only the earlier part of each inspired tidal volume enters the alveoli. The latter part of the inspired tidal volume

occupies the conducting airways and is termed the "dead space" volume, because it does not participate in gas exchange. Since the total volume expired per breath is the sum of the dead-space volume and the effective tidal volume, the composition of a complete expired breath represents a mixture of alveolar and dead-space gas and is determined by the composition and relative proportions of these two components (Otis, 1964). In the normal subject at rest and under steady-state conditions the ratio of dead space to tidal volume is less than thirty per cent (Comroe et al., 1962).

Most of the heat and water vapor exchange occurs in the upper respiratory tract. The exchange of carbon dioxide, oxygen, and nitrogen occurs in the alveoli by diffusion. In the normal lung under steady-state conditions the diffusion process is so adequate that the gases in the pulmonary venous blood leaving the alveoli are approximately in equilibrium with the gases in the alveoli.

Thus, the composition of the alveolar gas can be said to be determined by three principal factors: (1) the composition of the inspired gas, which is fixed by the environment; (2) the rates at which carbon dioxide and oxygen are exchanged between the blood and the alveolar gas which in the steady-state are determined by the oxidative metabolism of the body; and (3) the

alveolar ventilation (Otis, 1964).

Although at any moment there is a single value for the alveolar gas composition in an individual, in reality the composition of alveolar gas may vary widely from one alveolus to another so that this single value is for the average composition of the alveolar gases. Moreover, since ventilation constantly oscillates, any single value also reflects a temporal average.

Several factors, however, serve to minimize this temporal fluctuation. One of these is the functional residual capacity, which normally is several times larger than the alveolar tidal volume and thus serves to buffer changes in alveolar gas concentration. Another factor is the solubility of gases in the lung tissue itself which also buffers changes in alveolar gas concentration by making the equivalent lung volume larger than the actual volume of the gas phase. A third factor which minimizes fluctuations in alveolar gas composition is the cyclic variation in blood flow that occurs with breathing. Blood flow through the lungs rises to a maximum during inspiration and drops to a minimum during expiration, thus increasing gas exchange during the period when the lung volume is increasing and decreasing it when lung volume is decreasing.

CHAPTER III

REVIEW OF LITERATURE

Investigations of endotracheal aspiration which used physiological measurements were reviewed. Although a variety of variables were studied, no one study encompassed the wide range used in the present research. Findings of the studies reviewed were divided into the following categories, according to the results reported:

I. Arterial oxygen desaturation.
II. Atelectasis.
III. Cardiac arrhythmias and sudden death.

Arterial Oxygen Desaturation

During endotracheal aspiration, decreased arterial oxygen tension has been reported in a number of different categories of subjects and under various conditions. Moreover, several procedures and devices have been introduced to minimize this untoward effect of suction.

Studies Using Non-Human Subjects

When anesthetized and paralyzed dogs were suctioned without any concomitant oxygen administration, essentially

no change in arterial oxygen tension occurred. When 100 per cent oxygen was administered via side arm flow, however, arterial oxygen tension rose significantly. In dogs breathing 100 per cent oxygen spontaneously or apneic and hyperinflated with 100 per cent oxygen before suction, progressive decreases in arterial oxygen tension occurred during and after suction both with and without sidearm oxygen flows. As no control values were reported, it was not possible to determine either the extent to which arterial oxygen tension rose during 100 per cent oxygen administration prior to suction nor whether it fell below baseline values during suction (Fell & Cheney, 1971).

Studies Using Normal Subjects

Arterial oxygenation during and for three minutes after endotracheal suctioning was studied in anesthetized patients with no known pulmonary disease and with automatically controlled pulmonary ventilation (Boutros, 1970). Variables tested were the duration of suction, inspired oxygen tension prior to suction, and the fit of the suction catheter in the endotracheal tube. There were significantly greater decreases in arterial oxygen tension with prolonged suction and with suction than with similar periods of apnea. Patients breathing 25 per cent oxygen before suction had significantly greater decreases in arterial oxygen tension during suctioning than patients breathing 40 per cent oxygen. Full impaction

of the suction catheter in the endotracheal tube did not produce changes in arterial oxygen tension significantly different from those which occurred when the tube was not impacted. Hyperinflation sustained for ten seconds following suctioning resulted in significantly smaller relative decreases in arterial oxygen tension than no hyperinflation.

Other findings (Boba, Cincotti, Plazza, & Landmesser, 1959), however, do not substantiate the report that suction produces a significantly greater decrease in arterial oxygen tension than apnea. Although apnea of one minute's duration produced severe hypoxia in anesthesized normal subjects, the addition of endotracheal suction did not change significantly the incidence or degree of hypoxia. One explanation for this divergence in findings may be the difference in flow of the suction apparatuses used: 81 L per minute in the Boutros study as opposed to only 13 L per minute in the study by Boba et al. Theoretically, the faster the rate of flow through the suction catheter the faster the alveolar gas would be diluted with room air.

In addition, in anesthetized normal subjects, oxygen insufflation at a rate of 4 L per minute prevented hypoxia both during apnea alone and during apnea with simultaneous endotracheal suction (Boba et al., 1959). This rate of insufflation was used in conjunction with a suction withdrawal rate of 13 L per minute.

A sharp drop in arterial oxygen saturation was noted in one

anesthetized patient during endotracheal aspiration at the time of testing an arterial oximeter. This sharp drop occurred following administration of 20 per cent oxygen, but no hyperinflation nor side arm oxygen administration were used (Stephen, Slater, Johnson, & Sekelj, 1951).

Studies Using Patients Having Pulmonary Surgery

Data obtained by ear oximetry in eleven anesthetized patients undergoing pulmonary resection and being ventilated on 25 per cent oxygen showed that one minute of apnea resulted in arterial oxygen desaturation to or below 93 per cent in three-fourths of the trials (Downes, Wilson, & Goodson, 1961). Hyperventilation with oxygen for 15 seconds prior to apnea caused arterial oxygen saturation to remain above 95 per cent in every patient during two minutes of apnea with the pleura intact and during one minute of apnea with open pleura. Similar to the findings of Boba et al. (1959), endotracheal suction during apnea did not significantly affect changes in arterial oxygen saturation. Suction, in this study, was performed for 20 seconds during apnea with a catheter passed through the side arm of a connector and a negative flow rate of 13 L per minute.

Two methods were suggested to counteract the effects of endotracheal suction on arterial oxygen desaturation. Sustained

hyperinflations at twice tidal volume were needed to reverse the effects of 5 seconds of suctioning in patients undergoing thoracotomy (Boutros & Weisel, 1967). Whereas, in patients with cardiopulmonary disease undergoing abdominal surgery, use of a double-lumen suction catheter with oxygen flowing at 5 L per minute resulted in elevating arterial oxygen tensions during suction (Berman & Stahl, 1968). Endotracheal suctioning without any oxygen supplement lowered arterial oxygen tensions below room air values in the same patients.

Studies Using Post-operative Patients

Arterial oxygen tension measured before and after endotracheal suction at 28-30 L per minute in post-operative cardiac patients who were on ventilators and in a stable cardiovascular state showed a significant decrease. Changes during suction were greater if the patients had both cardiac disease and preoperative pulmonary hypertension. No patients returned to their pre-suction arterial oxygen tension levels after three minutes of ventilation at thirty three and one-third per cent oxygen (Taylor & Waters, 1971). No hyperinflation or supplemental oxygen administration were used. Similarly, in tracheotomized neurosurgical patients, arterial hypoxia lasted four minutes after suction (Schmidt, 1966).

Studies Using Patients in Respiratory Failure

In patients with respiratory failure on mechanical ventilation, two methods were used to counteract the effects of endotracheal suction. Hyperinflation with 100 per cent oxygen and limiting the suction period to 15 seconds produced mean values after fifteen seconds of suction higher than control measurements (Fell et al., 1971) and significantly different than those with no hyperinflation. Insufflation of 100 percent oxygen down a sidearm at 5 L per minute did not have any effect on the decreased arterial oxygen tension seen during suction. Suction of patients in acute respiratory failure without removing the ventilator, however, showed no significant difference from baseline values (Urban & Weitzner, 1969). Since Fell et al. (1971) did not find significant changes between baseline measurements and arterial oxygen tensions after suction of patients who did not receive hyperinflation with 100 per cent oxygen, the actual effect of the ventilator in the Urban et al. (1969) study can be questioned.

Atelectasis

Studies of infants (Brandstater & Muallem, 1969) subjected to tracheal suction produced a sharp fall in pulmonary compliance. The effects of suction on the lungs were greater when suction was

prolonged and when a larger suction catheter was used. Tidal volumes fell by amounts that ranged from 25 to 70 per cent of control. When infants were connected to the same respirator following suction with inflating pressure or tidal volume at the original setting, the lungs remained partially collapsed until a high pressure or large tidal volume was applied, sometimes up to 30 minutes after suction.

Adult subjects undergoing anesthesia also had significant decreases in lung-thorax compliance until several hyperinflations reversed the effects of suction (Egbert, Laver, & Bendixen, 1963). The effects on the lungs were attributed to the subatmospheric airway pressures produced by impaction of the catheter in the endotracheal tube (Rattenborg & Holiday, 1967; Saklad & Paliotta, 1967).

Prevention of sub-atmospheric airway pressure during suction was proposed by Segal (1965) through the use of endobronchial pressure during suction. Continuous use of mechanical ventilation during suction through an airway adaptor not only continued ventilation and prevented the development of sub-atmospheric pressures, but it also facilitated the removal of secretions by causing flow through the catheter to become more rapid.

Cardiac Arrhythmias and Sudden Death

Sudden unexplained deaths have occured in patients undergoing intensive treatment in hospitals during or soon after tracheal suctioning (Marx, Steen, Arkins, Foster, Joffe, Kepes, & Schapira, 1968; Case History, 1960; Dale, 1952). In patients with congenital malformation of the heart or myocardial disease, death occurred suddenly after the completion of aspiration through the endotracheal tube. It was hypothesized that aspiration through or withdrawal of the endotracheal tube at the close of the operation might conceivably have brought about cardiac arrest by effecting a transient state of decreased oxygen saturation with a resultant increase in susceptibility to vagal reflexes (Schumacker & Hampton, 1951).

In patients with lung disease, the incidence of transient cardiac arrhythmias during tracheal suction was significant (35 per cent) in patients who were breathing air prior to suction. Arrhythmias included frequent atrial premature contractions, nodal tachycardia, transient sinus arrest, incomplete heart block, and frequent premature ventricular contractions. After a brief period of breathing 100 per cent oxygen tracheal suctioning was no longer associated with significant arrhythmias (Shim, Fine, Fernandez, & Williams, 1969). Suctioning tracheotomized neurosurgical patients led to an increase of cardiac output, tachycardia, and decreased stroke volume (Schmidt, 1966).

CHAPTER IV

METHODOLOGY

The problem for this study was to explore the physiological determinants of a clinically successful method of endotracheal aspiration in patients with acute respiratory failure. In order to study this problem, the investigation was divided into two components: one to determine the magnitude of the changes of specific hemodynamic and respiratory variables which occurred during and after endotracheal aspiration in patients with acute respiratory failure and to examine whether any specific baseline measurement might serve as a predictor of the magnitude of these changes and therefore the degree of hazard; and second, to determine whether a standardized length of preoxygenation time provided adequate safety during tracheo-bronchial suction.

The methodology, which encompasses two separate designs, is divided into the following sections:

I. Definition of Terms

II. Design

III. Method

- A. Subject selection
- B. Criterion measures and instrumentation
- C. Procedure

Definition of Terms

Functional residual capacity (FRC) is the volume of gas remaining in the lungs at the resting expiratory level (Comroe et al., 1962).

Lung-thorax compliance (Static) (C_{L-T}) is the volume of change from baseline per unit of pressure change from baseline across the lung and chest wall as measured at the end inspiration no-flow period.

Inspired oxygen concentration (FI_{O_2}) is the fractional concentration of oxygen in the inspired gas (Comroe et al., 1962).

Arterial oxygen tension (Pa_{O_2}) is the partial pressure of oxygen in the arterial blood (Shapiro, 1973).

Arterial carbon dioxide tension (Pa_{CO_2}) is the partial pressure of arterial carbon dioxide (Shapiro, 1973).

Arterial pH (pHa) is the negative logarithm of the hydrogen ion concentration of the arterial blood (Shapiro, 1973).

Mixed venous oxygen tension ($P\bar{v}_{O_2}$) is the partial pressure of oxygen in the mixed venous blood (Comroe et al., 1962).

Mixed venous carbon dioxide tension ($P\bar{v}_{CO_2}$) is the partial pressure of carbon dioxide in the mixed venous blood (Comroe et al., 1962).

Mixed venous pH ($pH\bar{v}$) is the negative logarithm of the hydrogen ion concentration of the mixed venous blood.

Arterial oxygen saturation (Sa_{O_2}) is the saturation of the hemoglobin with oxygen in the arterial blood (Comroe et al., 1962).

Mixed venous oxygen saturation ($S\bar{v}_{O_2}$) is the saturation of the hemoglobin with oxygen in the mixed venous blood (Comroe et al., 1962).

Arterial oxygen content (Ca_{O_2}) is the concentration of oxygen in the arterial blood in ml O_2 per 100 ml of blood (Comroe et al., 1962).

Mixed venous oxygen content ($C\bar{v}_{O_2}$) is the concentration of oxygen in the mixed venous blood in ml O_2 per 100 ml of blood (Comroe et el., 1962).

Alveolar-arterial oxygen tension difference ($A\text{-}aD_{O_2}$) is the difference in partial pressure between oxygen in the alveolar air ($P_{A_{O_2}}$) and oxygen in the arterial blood (Pa_{O_2}) (Shapiro, 1973).

Physiologic shunt (Q_{VA}/Q_T) is that portion of the cardiac output that does not exchange with the alveolar air (Shapiro, 1973).

Physiological deadspace (V_D/V_T) is that portion of the mechanical ventilation that does not exchange with the pulmonary blood, i.e., wasted ventilation (Shapiro, 1973).

Suction sequence for this study is defined as a standardized method of suctioning which includes a 30 second period of hyperinflation with 100% O_2 prior to suction, a 20 second period of suction (including detachment from and reattachment to the ventilator), followed by another 30 second period of hyperinflation with 100% O_2.

Design

Two designs exist within this study--one an exploratory design and the other a one-group pretest-posttest design. To investigate the correlation between the magnitude of hemodynamic and respiratory changes during and after endotracheal aspiration and to examine whether any specific baseline measurement could serve as a predictor of the magnitude of these changes and therefore of the degree of hazard involved an exploratory design was used. This portion of the study was at the factor-relating level aimed at the production of correlational data.[5]

To determine the magnitude of changes of specific hemodynamic and respiratory variables which occurred during and after endotracheal aspiration a one-group pretest-posttest design was used (Campbell & Stanley, 1963). The form of the design is diagrammed as follows:

O X O

The O's represent the pretests and posttests administered to the experimental group. There was no control group.

Although Campbell and Stanley (1963) list the many weaknesses of this design, several factors must be taken into account which justify its use in this study. First, the internal validity is not jeopardized in that this study can be classified as a "laboratory experiment," as it was possible to literally take the laboratory

to the subject. Since in a laboratory experiment "the variance of all or nearly all of the possible influential independent variables not pertinent to the immediate problem of the investigation are kept to a minimum," it does have internal validity (Kerlinger, 1973, p. 398).

Neither is "instrument decay" a limiting factor, because all instruments used were calibrated immediately prior to each use. Since the time interval between the collection of the pretest and posttest data was short (less than one hour) and since the patients were judged to be stable during the data collection, it is thought that little change took place other than those related to the suctioning process. Since a control group was not used, however, it is not certain that no "maturation" took place (Campbell et al., 1963).

Each patient underwent an oxygen washin prior to the onset of the pretest data collection. After the washin, he or she was given approximately one half hour to equilibrate back to maintenance levels. It is hoped that in this way each patient received the same treatment during the pre-pretest period, i.e., had the same immediate pre-history.

Only one of the pretest measurements used, functional residual capacity, could have affected the outcome of the posttest measurements, as 100% oxygen was delivered in the measurement

of the FRC. Thus, this test was performed first and at least 20 minutes allowed for re-equilibration before other measurements were started. Data from another study (Suter, Fairely, & Schlobohm, 1975) show a return of FRC, compliance and shunt to baseline within 20 minutes.

Finally, as the subjects for this study were critically ill hospitalized patients, it was not possible ethically to use a control group, i.e., a group from which treatment was withheld simply for the sake of experimentation. Because the subject matter of the study is of significant importance to those concerned in the care of the critically ill, the use of a one group pretest-posttest design was more than justified.

Method

Subject selection. Eight adult patients from the Intensive Care Unite at San Francisco General Hospital were selected who had met the routine requirements for admission to the unit, i.e., their demonstrated need for intensive care. In addition, the following criteria were used for selection of each patient in that he or she had:

1. an endotracheal or nasotracheal tube in place;
2. continuous volume controlled ventilation;
3. systemic and pulmonary arterial catheters in place;
4. frequent suctioning routinely performed;

5. a stable enough condition, in the judgement of the investigator and physician in charge, to tolerate data collection.

Patients in acute respiratory failure are unable to meet the metabolic demands of the body for tissue oxygenation and carbon dioxide homeostasis (Shapiro, 1973). Thus, supportive ventilation, and at times oxygen therapy, is indicated. The use of an endotracheal tube allows for control of ventilation as well as for ease in the elimination of secretions by suctioning.

Because there are differences in the delivery of tidal volume by various types of ventilators, only patients on volume controlled ventilators were included in this study. Volume-cycled ventilators deliver a preset tidal volume, unless the pressure needed for delivery exceeds the setting of the safety valve. Thus, the minute volume is independent of moderate changes in compliance or resistance. Pressure-cycled ventilators, on the other hand, are cycled by pressure so that if the resistance increases or the compliance decreases, a critical level of pressure will be reached at a smaller tidal volume than with normal respiratory function (Nunn, 1969).

Although other variables affecting lung function, i.e., lung pathology, extent of trauma, other medical problems, medications and level of consciousness, were noted by the investi-

gator, they did not serve as selection criteria for the sample. The data gathered was expected to correlate on the basis of decrease in lung function regardless of the underlying pathology.

Criterion measures and instrumentation. The criterion measures selected were the most sensitive and reliable measures available to the investigator to measure lung function before, during, and after suction. These measures also had the advantage of being transportable to the bedside of the critically ill patient so that the routine care was not interrupted needlessly.

FUNCTIONAL RESIDUAL CAPACITY (FRC) was measured by the helium dilution technique for mechanically ventilated patients, according to the method of Suter and Schlobohm (1974). A description of the method as well as of the validity and reliability measures performed are presented in Appendix A.

LUNG-THORAX COMPLIANCE was calculated from translung-thorax (tracheal) pressures recorded on a strip recorder from a Harvard Apparatus pressure transducer and from tidal volumes recorded from the output of a wedge spirometer. An average of ten respiratory cycles was used for each measurement. A description of the method used and of the validity and reliability studies performed on the method can be found in

Appendix B.

VARIABLES OF GAS EXCHANGE were obtained from samples of arterial blood drawn from an indwelling femoral or radial arterial catheter or from samples of mixed venous blood drawn from an indwelling pulmonary arterial catheter. Each sample was drawn into a three ml sterile plastic disposable syringe in which the dead space and the needle had been filled with aqueous Heparin 1:1000. Clotting is prevented by heparin, and the volume of heparin left in the dead space of the syringe has been shown to be reasonably constant so that its effect on blood-gas tensions and pH may be ignored (Adams, Morgan-Hughs, & Sykes, 1967).

Immediately after withdrawal of the sample, each syringe was rotated between the palms of the hands to insure mixing of the heparin with the blood sample, any trapped air bubbles were dispelled, and the syringe was capped and placed in a bucket of ice. All samples were analysed within approximately one half hour of the time drawn.

There does not appear to be any serious problem due to diffusion of gases through the walls of plastic syringes for periods up to one hour (Adams et al., 1967). Oxygen tension values, however, do decrease progressively with time. Cooling the sample slows but does not stop the metabolic processes leading to oxygen utilization (Eldridge & Fretwell, 1965).

Simultaneous arterial and mixed venous samples were drawn by two persons over a one minute period with the use of a stop-watch. The rate of withdrawal of the pulmonary arterial sample did not exceed 3 ml per minute which is the fastest acceptable rate to preclude the withdrawal of arterialized blood (Suter, Lindauer, & Fairley, 1975).

Mixed expired CO_2 was obtained from analysis of the contents of a Douglas Bag in which the expired gas had been collected for approximately 3 minutes through the use of a Sierra valve connected to the endotracheal tube. Prior to the sample collection, the Douglas bag was washed twice with the subject's expired gas and volume in the bag returned to zero through the application of suction and the rotation of the inlet valve.

Blood and gas samples were analysed in the specialized laboratory adjacent to the ICU by either a laboratory technician or by the research technician. A description of the equipment used and the calibration procedures is included in Appendix C.

Blood samples were analysed for pH, P_{CO_2}, and P_{O_2} at STPD and for hemoglobin. Values were then corrected to each subject's temperature and to the barometric pressure at the time of the sampling through use of a Hewlett-Packard #9810 desk computer program. The correction calculations are included in Appendix D.

From the blood gas data obtained, other respiratory variables were calculated: $A\text{-}aD_{O_2}$ (Appendix E), $A\text{-}VD_{O_2}$, Q_{VA}/Q_T (Appendix G), and V_D/V_T (Appendix F). From the blood gas values and from the mixed expired CO_2 sample, CO_2 production (Appendix H), alveolar minute volume (V_A) (Appendix I), and cardiac output (Q_T) by the CO_2 production method (Appendix J) were calculated.

Procedure. Each morning the patients in the ICU were assessed by the investigator to determine if any met the criteria for the study. After having selected a patient, the physician in charge of the unit was approached for his consent to conduct the investigation on that patient, according to the regulation of the University of California Committee on Human Experimentation. (The consent form is included in Appendix K). The patient was then asked for his verbal consent, if he was conscious, or his next of kin was asked to sign a consent form if he was not capable. (The consent form for next of kin is included in Appendix L). In addition, a patient information guide was completed on each patient (Appendix M).

All equipment used in the study was prepared in the laboratory and brought to the patient's bedside ready for use. Calibrations were performed at the bedside immediately prior to use.

All subjects were placed in the supine position, either flat or no higher than 45^{o} for the entire duration of the study, as

position has been shown to affect lung function. In changing from the sitting to the supine position blood flow distribution changes in the lungs (West, 1974), the diaphragmatic fraction of the tidal volume increases (Wang & Josenhans, 1971), and pulmonary extravascular water increases (Marshall, Teichner, Kallow, Sugerman, Wyche, & Tantum, 1971). Conversely, in changing from the supine to the sitting position, deadspace increases (Larson & Severinghaus, 1962).

OXYGEN WASHIN was performed approximately one hour prior to the suctioning sequence. At the start of the washin, each patient's ventilator was changed to one and one-half the maintenance tidal volume (not exceeding a maximum of 20 ml per Kg) and to an FI_{O_2} of 1.0. Using a multi-stopcock manifold, loaded with heparinized syringes, serial 1 ml systemic arterial blood samples were drawn at ten second intervals for the first minute, at fifteen second intervals for the second minute, and thereafter at thirty second intervals for three minutes. Two persons were used for this sequence--one to control the ventilator and to time the sampling with a stopwatch and the other to draw the arterial samples. Each 1 ml sample was analysed for Pa_{O_2} only.

PRE-SUCTION control measurements were made beginning approximately one-half hour prior to suction in the following order:

1. Functional residual capacity

2. Lung-thorax compliance
3. Mixed expired CO_2 and minute volume
4. Simultaneous systemic arterial and pulmonary arterial samples.

SUCTION SEQUENCE. A control arterial sample was drawn and then the patient's ventilator was changed to a tidal volume of one and one-half the maintenance level (the same hyperventilation as used for the oxygen washin) and the FI_{O_2} was changed to 1.0. Using a multi-stopcock manifold, loaded with heparinized syringes, serial systemic arterial samples were drawn during the sequence. The first sample was drawn at the end of 30 seconds of hyperinflation with 100% O_2, and then at 5 second intervals during 20 seconds of endotracheal suction, at 10 second intervals during a 30 second period of post-hyperinflation with 100% O_2 and 30 second intervals for the next minute and then at one minute intervals for the next 3 minutes.

The suctioning sequence was held standard for all subjects and simulated that which is common practice in a number of Intensive Care Units. Although some procedures for suctioning specify the use of an anesthesia bag for the delivery of hyperinflation with 100% O_2 before and after suction, the ventilator was used for this study in order to have control over the volume delivered. Also, even though in some settings several periods of suctioning are performed in rapid succession, in this study only

one suction period was used in order not to have a multiple effect of several sequences superimposed upon one another.

POST-SUCTION measurements were begun immediately after the cessation of the suction sequence and lasted approximately one half hour. Measurements were made in the following sequence:

1. Simultaneous systemic arterial and pulmonary arterial samples.
2. Mixed expired CO_2 and minute volume.
3. Lung-thorax compliance.
4. Functional residual capacity.

CHAPTER V

RESULTS OF THE STUDY

Results of the study are presented in four sections. The first section illustrates the nature of the eight sample patients. Three subsequent sections present findings related to each of the objectives of the study: (1) the magnitude of changes of specific hemodynamic and respiratory variables which occur during and after endotracheal aspiration; (2) the correlation between the magnitude of hemodynamic and respiratory changes during and after endotracheal aspiration and their physiological status prior to aspiration; and (3) the safety of a standardized period of pre-oxygenation time.

Nature of the Sample

The sample for the study consisted of eight subjects who were selected over a five month period from the patient population of the Intensive Care Unit of San Francisco General Hospital. Each subject selected met the five criteria for selection in that he or she had: (1) an endotracheal tube in place; (2) continuous volume controlled ventilation; (3) systemic and pulmonary arterial

catheters in place; (3) frequent suctioning routinely performed; and (4) a stable enough condition, in the judgement of the investigator and physician in charge, to tolerate the data collection.

Sex

Five men and three women comprised the sample for this study.

Age

Ages of the sample ranged from 23 to 82 years with a mean age of 55.5 ± 19.4 (Mean ± SD). Male subjects' ages ranged from 23 to 82 years with a mean age of 54.8 ± 25.2, while female subjects' ages ranged from 50 to 64 years with a mean age of 56.7 ± 7.0.

Diagnoses

All subjects in the study were in acute respiratory failure, i.e., they had a "disorder of the respiratory mechanism severe enough to cause arterial blood gas abnormality" (Fairley, 1976). In addition, three subjects had suffered multiple trauma which had resulted in numerous fractures among which were rib fractures. One of these multiple trauma patients had a hemopneumothorax and another atelectasis. Two patients

were diagnosed as having pneumonia. One who had overdosed on a variety of medications had aspiration pneumonia, and the other had pneumonia from gram negative diplococci. Another subject had bilateral pleural effusion.

Three subjects were post-operative from exploratory laparotomies. One of these had an abdominal abscess drained which had resulted in septicemia, while the other two had negative abdominal findings.

All the subjects studied had numerous medical problems besides those of respiratory origin (See Table 1). These problems, although indirectly affecting respiratory function, remained constant throughout the measurement period on each subject. All subjects, except the first one studied, had disease severe enough to cause death later in their ICU course.

Ventilatory Status

Baseline measurements were made with the same ventilation at which each patient was being maintained prior to the study, i.e., that at which optimum arterial oxygen and carbon dioxide levels for that patient were maintained. All subjects were mechanically ventilated on controlled ventilation at levels of oxygen above room air though none was

Table 1

Descriptive Data on Subjects

Subject	Sex	Age	Etiologic Factors Leading to Respiratory Failure
1	F	50	Laparotomy, hyponatremia, rheumatoid arthritis, and pericarditis
2	M	47	Pneumonia, atrial fibrillation, and fever
3	F	64	Multiple trauma: rib fractures with right hemopneumothorax, occipital skull fracture, right clavical fracture, occipital laceration, glycosuria, hematuria and pyuria, pulmonary hypertension, and hypertension
4	F	56	Laparotomy and drainage of abscess, septicemia, renal failure, metabolic acidosis, and hypotension
5	M	82	Bilateral pleural effusion, metabolic acidosis, congestive heart failure and atrial fibrillation, and liver disease with jaundice
6	M	23	Overdose and aspiration pneumonia, and lacerated right wrist
7	M	79	Multiple trauma: third left rib fracture, atelectasis, left parietal skull fracture, ulnar fracture, gram negative septic shock, possible myocardial infarction
8	M	43	Multiple trauma: left rib fracture, left tibia fracture, negative laparotomy, and cirrhosis with DT's

higher than 50 per cent O_2 (See Table 2). The Ohio 560 ventilator was used in all cases except one in which the Searle ventilator was used.

Arterial carbon dioxide tensions were below 35 torr in all subjects, with the lowest being 25 torr. Only two subjects had baseline arterial oxygen tensions above 100 torr. One of these, Subject 3, had an arterial oxygen tension of 146 torr on 50 per cent inspired oxygen.

Cardio-respiratory variables calculated from the systemic and pulmonary arterial gas values are summarized in Table 3. At baseline all subjects showed some degree of intrapulmonary shunt ($\dot{Q}_{VA}/\dot{Q}_T$), ranging between 13 and 53 per cent of cardiac output. Likewise, the difference between alveolar and arterial oxygen tensions ($A\text{-}aDO_2$) ranged from 124 to 262 torr, while the difference between arterial and venous oxygen contents ($a\text{-}vDO_2$) ranged from 2.7 to 6.1 ml%. Physiologic dead space ranged from 30 to 50 per cent of tidal volume.

Functional residual capacity in all subjects was below the value predicted for age, sex, and body surface area (Comroe et al., 1962, p. 325) (See Figure 1). Values ranged from 1251 ml to 3174 ml. Lung-thorax compliance measurements ranged from 25 to 66 cm H_2O.

Table 2

Baseline Ventilation of Subjects

Subject	Ventilator	FIO_2	V_T (ml/Kg)	EEP[a] (cm/H_2O)	Pa_{O2} (torr)	Pa_{CO2} (torr)
1	Ohio 560	0.25	13.9	0	90	
2	Ohio 560	0.40	11.1	0	81	29
3	Searle	0.50	10.2	0	146	31
4	Ohio 560	0.50	13.2	10	53	35
5	Ohio 560	0.48	11.4	0	76	25
6	Ohio 560	0.40	12.5	10	82	27
7	Ohio 560	0.38	12.8	0	109	32
8	Ohio 560	0.38	9.8	5	48	30

[a]End expiratory pressure

Table 3

Subjects' Baseline Respiratory Status[a]

Subject	V_D/V_T	$A\text{-}aDO_2$ (torr)	$a\text{-}vDO_2$ (ml%)	$\dot{Q}_{VA}/\dot{Q}_T$	FRC (ml)	C_{LT} (ml/cm H_2O)
1[b]					2440	26
2	0.49	174	6.1	0.13	3174	46
3	0.42	173	4.2	0.16	1251	25
4	0.50	262	3.3	0.53	1580	25
5	0.50	240	4.9	0.16	1660	55
6	0.25	173	3.8	0.19	1599	49
7	0.37	124	3.2	0.14	1518	66
8[c]	0.30	190	2.7	0.45		33
Mean ± SD						

[a]Physiologic deadspace (V_D/V_T) and intrapulmonary shunt ($\dot{Q}_{VA}/\dot{Q}_T$) are expressed as fractions of tidal volume and total cardiac output respectively. Alveolar-arterial oxygen tension difference ($A\text{-}aDO_2$) is expressed in torr.

[b]Subject's pulmonary arterial line became non-functional so that no mixed venous gas values were available.

[c]No FRC measurements were made on this subject because of equipment malfunction.

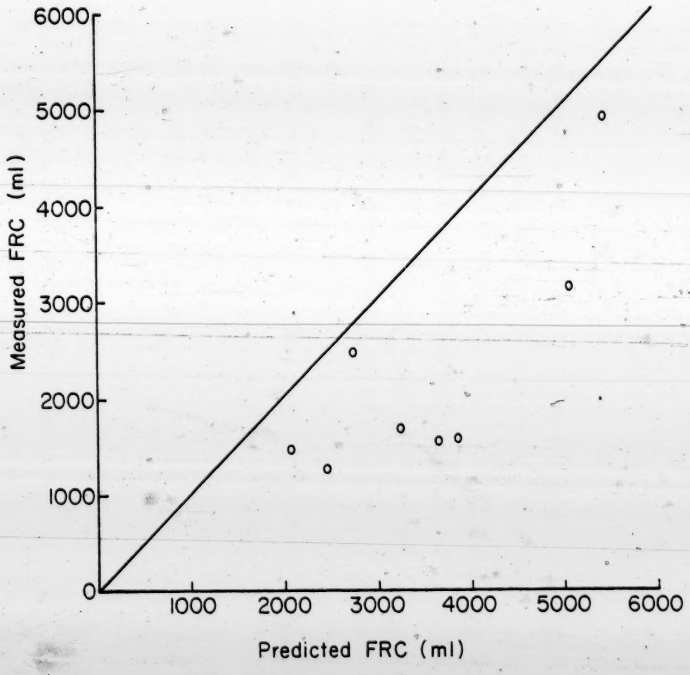

Figure 1. Resting FRC measured on each subject compared with predicted normal supine value. In all cases the measured FRC was lower than the predicted.

Intubation

All subjects had indwelling Lanz Controlled Pressure Cuff Endotracheal Tubes. Suction was performed through Bard Parker #14 F. suction catheters connected to wall suction in the Intensive Care Unit. Ratios of the external diameter of the suction catheters to the internal diameter of the endotracheal tubes are presented in Table 4. In this study, the ratio of the external diameter of the suction catheter to the internal diameter of the endotracheal tube ranged from 0.33 to 0.43, below the 0.5 ratio recommended as safe to prevent the development of negative pressure in the trachea (Rosen et al., 1962).

Suction was measured in liters per minute of flow through an unoccluded catheter by attachment to a Wright Spirometer. Flows ranged from 16.8 to 30.1 L/minute. This variation was due to the different suction apparatus used. There was no significant statistical correlation between the per cent change in arterial oxygen tension during suction and the flow rate of the suction catheters.

Table 4

Conditions of Suction

Subject	E. D. of suction catheter[a] / I. D. of E. T. tube	Suction (L/min.)
1	0.43	16.8
2	0.33	29.0
3	0.33	31.0
4	0.43	25.0
5	0.38	19.2
6	0.43	26.0
7	0.38	22.3
8	0.38	30.1

[a]External diameter of the suction catheter / Internal diameter of the endotracheal tube

Results Related to Objective 1

Objective 1

The first objective of the study was as follows:

To determine the magnitude of changes of specific hemodynamic and respiratory variables which occur during and after endotracheal aspiration in patients with acute respiratory failure.

Data for eight subjects from baseline and post-suction measurements were compared using paired t-tests (Table 5). The only significant changes found were an increased arterial oxygen tension after suction ($p < 0.05$). Changes in all other variables studied were found statistically non-significant.

A number of variables remained relatively unchanged between measurements made before and after suction, i.e., arterial and mixed venous pH and arterial carbon dioxide tension and bicarbonate levels. Mixed venous oxygen tension rose in five of the seven subjects studied, remained the same in one, and decreased slightly in one subject. The saturation of arterial oxygen rose in all subjects, although this rise was not statistically significant. Mixed venous oxygen saturation similarly rose in all subjects, except one where it fell slightly. Arterial oxygen content rose or

Table 5

Variables Measured Before and After Suction[a]

Variable Measured	n	Mean and Standard Error Pre-suction	Post-suction	Difference
PHa	7	7.43± 0.05	7.43± 0.04	0.00
$PaCO_2$	7	29.86± 1.24	29.14± 2.96	0.72
PaO_2	7	85.00± 12.72	96.43± 14.48	-11.43**
SaO_2	7	91.80± 3.41	94.14± 2.22	- 2.34
H_{CO_3} a	7	19.85± 1.80	18.92± 1.92	0.93
O_2 content[a]	7	12.36± 0.57	12.55± 0.50	- 0.19
$p\bar{H}v$	7	7.39± 0.04	7.40± 0.04	- 0.01
$P\bar{v}CO_2$	7	34.00± 1.50	30.29± 2.51	3.71
$P\bar{v}O_2$	7	33.00± 1.90	36.29± 1.49	- 3.29
$S\bar{v}O_2$	7	61.05± 4.71	67.69± 2.29	- 6.64
$HCO_3\bar{v}$	7	20.57± 1.71	18.53± 2.15	2.04
O_2 content $\bar{v}$	7	8.30± 0.52	8.60± 0.55	- 0.30
$a\text{-}vD_{O_2}$	7	4.05± 0.44	3.97± 0.56	0.08
$A\text{-}aD_{O_2}$	7	191.03± 17.45	182.20± 16.61	8.83*
$\dot{Q}_{VA}/\dot{Q}_T$	7	0.24± 0.06	0.25± 0.06	- 0.01
V_D/V_T	7	0.40± 0.04	0.45± 0.06	- 0.05
$\dot{V}_{CO_2}$	7	228.70± 35.26	214.09± 43.26	14.61
FRC	6	1913.20±303.00	1833.30±318.30	79.90
C_{LT}	8	40.62± 5.53	41.62± 6.11	- 1.00
$\dot{Q}_T$	7	7.59± 1.80	8.38± 3.20	- 0.79

* Significant @ 0.05; ** significant @ 0.005.

[a] Values obtained from simultaneous samples drawn before and after suction.

remained the same in all subjects, while mixed venous oxygen content rose in six subjects and fell in one. Mixed venous carbon dioxide tension fell in all subjects, except one, after suction.

Physiologic deadspace increased after suction in five subjects studied and decreased in two. Arterial-to-venous oxygen tension and intrapulmonary shunt both decreased and increased after suction, so that mean values for each remained the same. Cardiac output (by $\dot{V}_{CO_2}$) decreased in all subjects, except one, after suction. When data from that one subject (who had an exceptionally high cardiac output of 16 to 26 L/minute) was not included in the analysis, there was a statistically significant decrease in cardiac output after suction ($p < 0.025$).

Functional residual capacity and lung thorax compliance both increased and decreased after suction. There was no pattern of similar increases or decreases between them.

Findings Related to Objective 2

Objective 2

The second objective of the study was as follows:

To investigate in patients with acute respiratory failure the correlation between the magnitude of changes in hemodynamic and respiratory variables during endotracheal aspiration and their status prior to aspiration.

Findings

Arterial oxygen tension was significantly increased after suction over baseline values ($p < 0.005$). Alveolar-to-arterial oxygen difference was significantly decreased ($p < 0.05$). There was no significant change in any other variable studied when pre-suction and post-suction values were compared with a paired t-test (See Table 5).

Arterial oxygen tension was measured also from serial blood samples drawn during the suction sequence: baseline, hyperinflation with 100 per cent oxygen for 30 seconds, suction for 20 seconds, hyperinflation with 100 per cent oxygen for 30 seconds, and return to maintenance. An example of one series of arterial oxygen tensions during the suction sequence of one subject (Subject 1) is shown in Figure 2. In this subject arterial oxygen tension did not fall below baseline during the entire suction sequence.

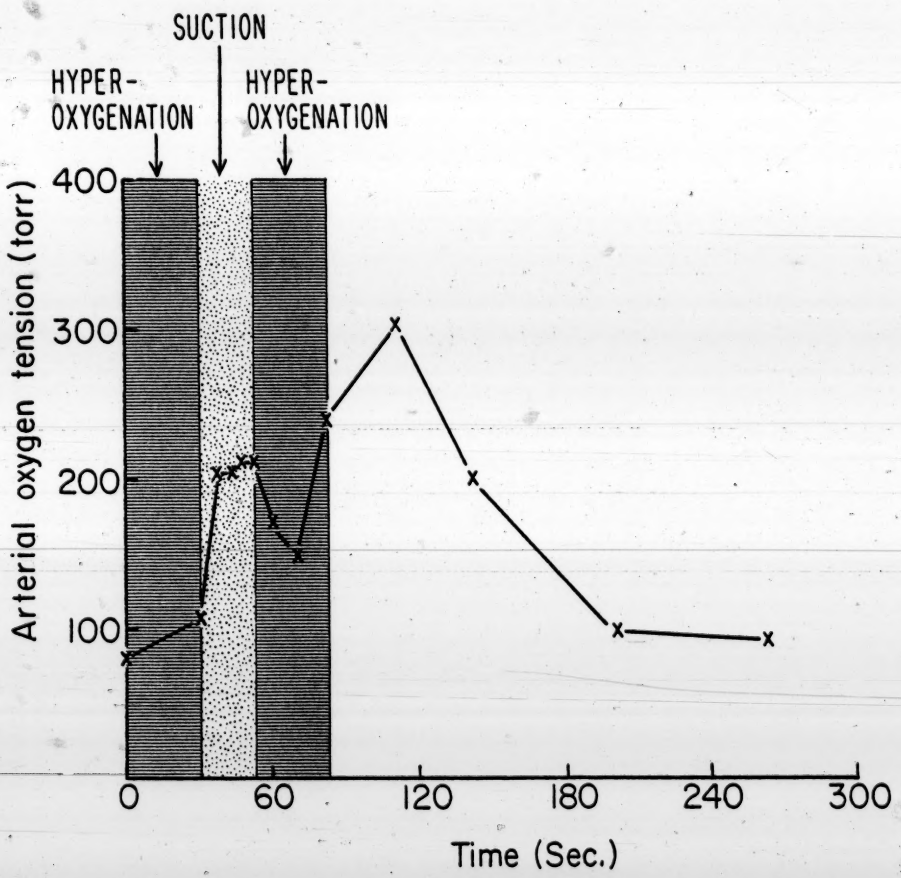

Figure 2. A series of arterial blood oxygen tensions during the suction sequence of one subject (Subject 1). In this subject whose resting FRC was 89% of the predicted normal supine value, PaO_2 rose 26 torr during the pre-hyperinflation with 100% O_2, rose 104 torr during the 20 second suction period, fell 60 torr during post-hyperinflation with 100% O_2, and remained 11 torr above baseline after 3 1/2 minutes of maintenance ventilation.

In order to identify a clinical measurement which would predict the change in PaO_2 during the suction sequence in a particular subject, a number of variables were examined which were thought to affect the change in arterial oxygen tension during the suction sequence. These variables were examined in relation to the per cent change in PaO_2 during the suction sequence after the initial period of hyperpreoxygenation and hyperventilation. The per cent change in PaO_2 during the suction sequence was calculated as follows:

$$\frac{PaO_2 \text{ at lowest point}}{PaO_2 \text{ at baseline}} \times 100 - 100 = \% \text{ change in } PaO_2 \text{ during suction sequence}$$

Percentage changes in PaO_2 values for each subject are presented in Table 6. Values range from -29% to +88% in the eight subjects studied.

Only two cardio-respiratory variables measured were significantly correlated to the per cent change in PaO_2 during the suction sequence--the per cent of oxygen washin after 30 seconds and the rate of washin of Phases I & II of the oxygen washin curve (See Table 7).

Since the standard period of hyperinflation with 100% oxygen prior to suction in this study was 30 seconds, the per cent of total washin at thirty seconds was calculated

Table 6

Per Cent Change in Arterial Oxygen Tensions

During the Suction Sequence

Subject	Baseline PaO_2	Lowest PaO_2	Per Cent Change in PaO_2[a]
1	80	150	+88
2	97	121	+25
3	146	206	+41
4	53	51	- 4
5	76	98	+29
6	82	58	-29
7	109	143	+31
8	47	53	+13
Mean $\pm$ S.E.	86.2 $\pm$ 11.2	110 $\pm$ 19.6	24.2 $\pm$ 12.1

[a]Using the baseline PaO_2 as 100%, per cent change in PaO_2 during the suction sequence is expressed as a value plus or minus baseline and calculated as

$$\frac{PaO_2 \text{ at lowest point}}{PaO_2 \text{ at baseline}} \times 100 - 100.$$

Table 7

Correlation Coefficients (r) between Variables Thought to Affect Arterial Oxygen Tension During the Suction Sequence and the Per Cent Change in Arterial Oxygen Tension

Variables Measured	n	Correlation Coefficient to % Change in PaO_2 During Suction Sequence
FIO_2	8	-0.513
PaO_2	8	0.308
SaO_2	8	0.413
$A\text{-}aDO_2$	7	-0.227
$a\text{-}vDO_2$	7	0.324
$\dot{Q}_{VA}/\dot{Q}_T$	7	-0.400
C.I.	7	-0.314
V_D/V_T	7	0.486
$\dot{V}_{ALV.}/m^2$	7	-0.534
FRC as % predicted	7	0.628
Specific C_{LT}	7	0.338
Rate of Washin Phase I & II	8	0.719*
Phase II	8	0.611
Phase III	8	0.001
% Washin of O_2 at 30 seconds	8	0.799*

*Significant @ 0.05

as follows:

$$\frac{PaO_2 \text{ at 30 seconds}}{PaO_2 \text{ at peak level}} \times 100 = \% \text{ washin at 30 seconds}$$

Data for this variable, the per cent washin at 30 seconds, are presented in Table 8. In the subjects studied the per cent washin at 30 seconds ranged from 27 to 69 per cent.

To determine if the per cent washin at 30 seconds was a predictor of the per cent change in PaO_2 during the suction sequence, a correlation and least squares regression were performed. The per cent washin at 30 seconds accounted for 64 per cent of the variance of the per cent change in arterial oxygen tension during the suction sequence ($r^2 = 0.638$, $p < 0.01$) and in the subjects studied predicted the per cent change in PaO_2 during the suction sequence according to the regression formula:

$$\begin{array}{l}\text{\% change in } PaO_2 \\ \text{during the} \\ \text{suction sequence}\end{array} = 1.9 \begin{array}{l}\text{\%washin} \\ \text{at 30 seconds}\end{array} + (-56.3)$$

(See Figure 3)

The other variable which was significantly correlated to the per cent change in PaO_2 during the suction sequence was the rate of washin of oxygen of Phases I and II combined. (An

Table 8

Per Cent of Oxygen Washin After 30 Seconds of Hyperventilation with 100 Per Cent Oxygen[a]

Subject	PaO_2 at 30 sec.	PaO_2 at peak	% O_2 washin at 30 sec.
1	251	366	69
2	155	371	42
3	196	376	52
4	69	153	45
5	91	253	36
6	94	354	27
7	130	388	34
8	64	237	27
Mean ± S.E.	131 ± 23	312 ± 31	42 ± 5

[a]Hyperventilation was at one and one half the maintenance tidal volume for each subject. Timing of the 30 second period started when the ventilator of each subject was changed to hyperventilate at 100% O_2. Thus, the 30 second time period included both system lag time in ventilator change over and circulation lag time of each subject.

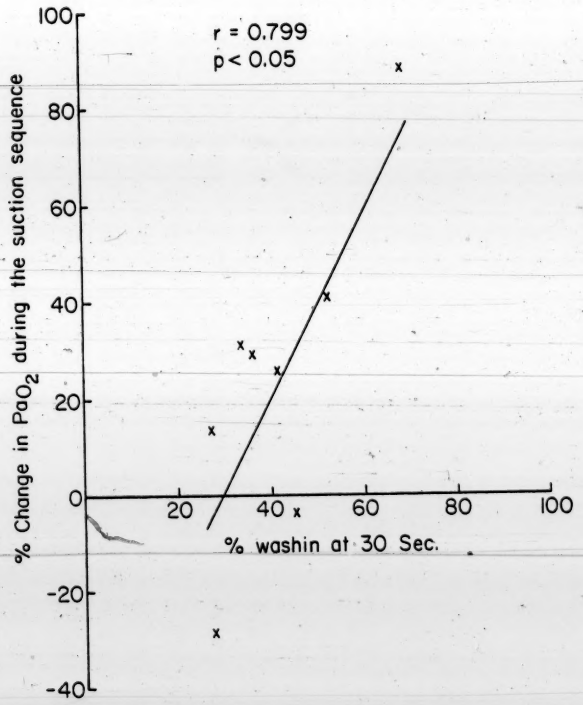

Figure 3. The relationship between the per cent of oxygen washin at 30 seconds and the per cent change in PaO_2 during the suction sequence. The % washin at 30 seconds = $\frac{PaO_2 \text{ at 30 seconds}}{PaO_2 \text{ at peak level}} \times 100$. The % change in PaO_2 during the suction sequence = $\frac{PaO_2 \text{ at lowest point}}{PaO_2 \text{ at baseline}} \times 100 - 100$.

explanation of the derivation of Phases I and II will be presented in Section 3 of this chapter.) The rate of washin of Phases I and II accounted for 52 per cent of the variance of the percent change in PaO_2 during the suction sequence ($r^2 = 0.517$). In the subjects studied, the per cent change in PaO_2 during the suction sequence can be predicted according to the regression formula:

$$\begin{array}{l}\text{\% change in } PaO_2 \\ \text{during the} \\ \text{suction sequence}\end{array} = 19.9 \begin{array}{l}\text{rate of} \\ \text{washin of} \\ \text{Phases I \& II}\end{array} + (-14.8)$$

(See Figure 4)

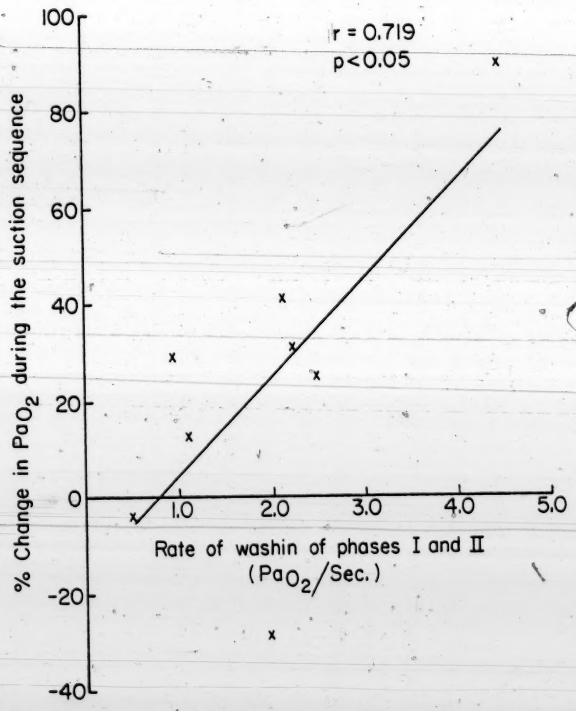

Figure 4. The relationship between the rate of oxygen washin of Phases I and II (ΔPaO_2/second) and the per cent change in PaO_2 during the suction sequence.

Findings Related to Objective 3

Objective 3

The third objective for the study was as follows:

To determine whether a standardized length of preoxygenation time provides adequate safety during tracheo-bronchial suction or whether a clinical index, e.g., compliance, would serve as an appropriate guide to the length of time necessary to prevent hypoxemia.

Findings

In order to determine whether a thirty second period of hyperinflation with 100% oxygen is adequate to prevent hypoxemia during tracheo-bronchial suction, the ventilation and circulation effects were evaluated by measuring arterial oxygen tensions during a five minute period of hyperinflation with 100% oxygen at one and one half the maintenance tidal volume.

Oxygen washin data for one subject (Subject 1) are presented in Figure 5. Using the highest arterial oxygen tension recorded as 100 per cent washin, this subject reached 100 per cent washin at 3 minutes and 69 per cent of the total washin at 30 seconds. The washin time was measured from the point at which the ventilator was turned from maintenance

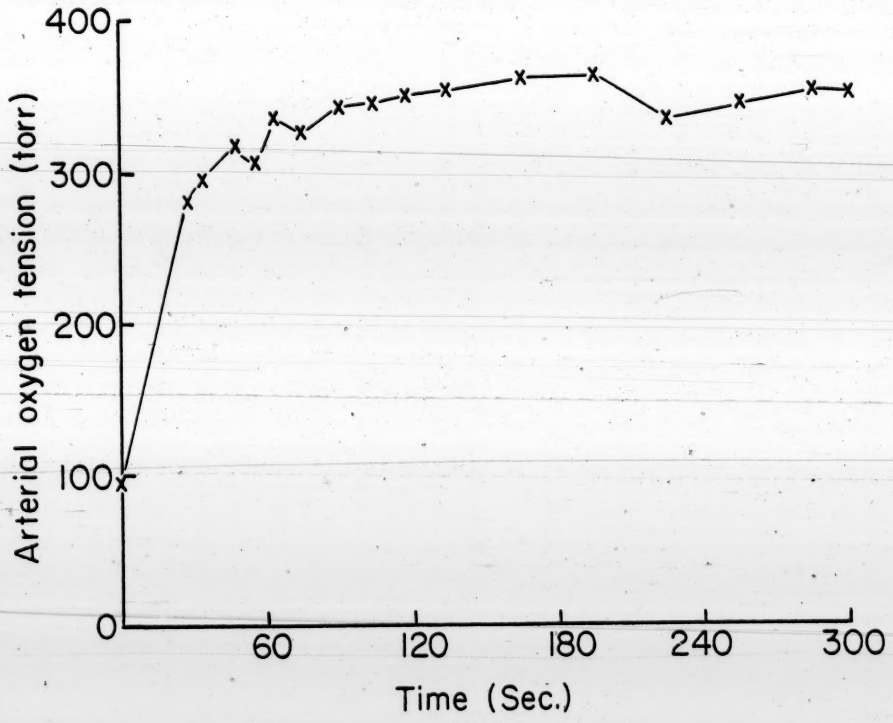

Figure 5. Oxygen washin curve for Subject 1. Arterial oxygen tension reached its peak level at 3 minutes of washin (100%). By the end of the conventional 30 second washin prior to suction, it had reached 69% of total washin.

tidal volume to one and one half maintenance and the inspired oxygen tension from maintenance to 100 per cent. Thus, the washins recorded reflect multiple patient factors, including ventilator dead space washout, FRC, minute ventilation, $\dot{Q}_S/\dot{Q}_T$, $\dot{Q}_{VA}/\dot{Q}_T$, $\dot{Q}_T$, lung N_2, blood N_2, and respiratory quotient.

The washin of oxygen at 30 seconds was compared to the total washin of oxygen for each subject. Results are presented in Table 8. The per cent washin as measured by arterial oxygen tension levels was calculated by:

$$\frac{Pa_{O_2} \text{ at 30 seconds}}{Pa_{O_2} \text{ at peak level}} \times 100 = \% \text{ washin at 30 seconds}$$

In the subjects studied the per cent washin at 30 seconds ranged from 27 to 69 per cent.

Because the first 30 seconds of oxygen washin reflect both the system lag time of the ventilators used and the circulation lag time of each subject, data for oxygen washin were further analysed in order to determine factors which affected each stage of the entire washin process. Since washin curves are usually exponential, in order to facilitate analysis by linearizing the O_2 washin curves all arterial oxygen tensions were converted to their logarithms

and plotted over time.

The oxygen washin curves had four distinct components, as exemplified by the oxygen washin curve for Subject 3 (See Figure 6), though each patient's curve did not necessarily contain all four components. These components were divided into phases: Phase I--the initial plateau; Phase II-- the fast filling component; Phase III--the slow filling component; and Phase IV--the reabsorption component.

Phase I. Since timing of the oxygen washin began with the change of the ventilator to hyperventilate at 100 per cent oxygen, the first phase of the oxygen washin curve in some subjects consisted of a plateau in arterial oxygen tension before the increased oxygen tensions were apparent at the sampling site. This sampling site was the same for all subjects measured--femoral arterial catheter. The same amount of plastic tubing was used for each subject in connecting the femoral catheter to the serial stopcocks and syringes.

Phase II and Phase III. Curves for all subjects exhibited both Phase II and Phase III. These data indicated that the lungs behaved as if composed of two compartments ventilating at different exchange rates, a fast exchange compartment (Phase II), in which in the eight subjects studied ventilation was measured by change in PaO_2 at a mean rate

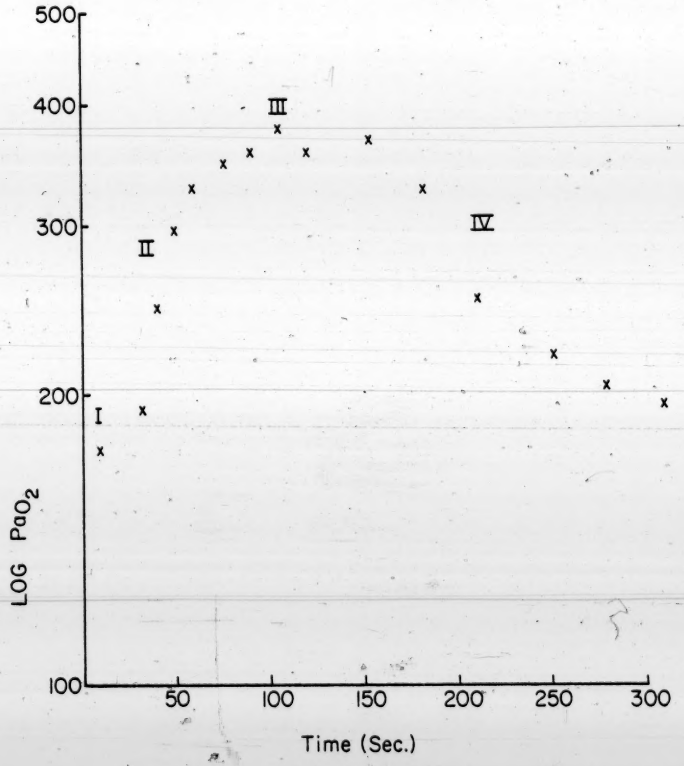

Figure 6. Oxygen washin curve for Subject 3, showing all four phases of the washin: Phase I--the initial plateau; Phase II--the fast filling component; Phase III--the slow filling component; and Phase IV--the reabsorption component.

of 2.38 ± 0.43 (ΔPaO_2/second) (Mean ± S.E.), and a slow exchange compartment (Phase III), in which in the subjects studied ventilation as measured by change in PaO_2 at a mean rate of 0.28 ± 0.03 (ΔPaO_2/second) (See Table 9).

Phase IV. Observed in only two subjects, Phase IV represents a decrease in arterial oxygen tension during the latter portion of the five minute oxygen washin curve at a mean rate of -0.15 ± 0.13 (ΔPaO_2/second).

Predictors of the rate of washin. In order to identify a clinical measurement which would predict the rate of washin to be expected in a particular subject, a number of variables were examined which were thought to influence the washin of gases. These variables were examined in relation to the rates of washin in Phases I, II, and III (See Table 10).

Phase I and Phase II were combined because although Phase I was determined by both ventilator and circulation lag times, its duration definitely affected the start of the rapid washin phase (Phase II), and because Phase I alone did not encompass the entire 30 second standard hyperpre-oxygenation time.

Three variables were negatively correlated with the rate of washin of Phase I & II-- FIO_2, A-aDO_2, and $\dot{Q}_{VA}/\dot{Q}_T$ (See Table 10). The lower the starting inspired oxygen

Table 9

Rate of Change in Arterial Oxygen Tension

in Four Phases of Oxygen Washin (ΔPaO_2/second)

Subject	Phases			
	I	II	III	IV
1	0	4.47	0.32	-0.14
2	0	2.49	0.24	0
3	-0.65	3.11	0.27	-1.06
4	0	0.67	0.16	0
5	0	1.24	0.25	0
6	0.17	2.83	0.36	0
7	0.30	2.66	0.23	0
8	0.17	1.53	0.39	0
Mean $\pm$ SE	-0.001 $\pm$ 0.1	2.38 $\pm$ 0.43	0.28 $\pm$ 0.03	-0.15 $\pm$ 0.13

Table 10

Correlation Coefficients (r) Between Variables Thought to Affect the Rate of Washin and the Rate of Washin of Phases I, II, and III.

Phase	FIO_2	$A\text{-}aDO_2$	$\dot{Q}_{VA}/\dot{Q}_T$	C.I.	V_D/V_T	$\dot{V}_{ALV.}/m^2$	FRC	C_{LT}
I & II	-0.803*	-0.964*	-0.786*	-0.311	-0.230	-0.182	0.508	-0.110
II	-0.699	-0.848*	-0.740	-0.270	-0.434	-0.192	0.030	-0.105
III	-0.510	-0.336	-0.032	-0.374	-0.831*	-0.474	0.063	-0.076

*Significant at 0.05

concentration (See Figure 7), the lower the starting alveolar-to-arterial oxygen tension difference (See Figure 8), and the lower the starting shunt fraction (See Figure 9), the faster the oxygen washin of Phases I & II occurred. These three variables accounted for 65 per cent, 75 per cent, and 62 per cent respectively of the the variance of the rate of washin of Phases I & II (See Table 11).

When the combined effects of FIO_2 and $A\text{-}aDO_2$ were regressed on to Phase I & II, according to the regression formula calculated from the data of seven subjects:

$$\text{Rate of Washin of Phases I \& II } (\Delta PaO_2/\text{sec.}) = -0.01\,(A\text{-}aDO_2) + 3.7(FIO_2) + 3.33$$

$$[r = 0.78,\ p < 0.05]$$

$A\text{-}aDO_2$ and $\dot{Q}_{VA}/\dot{Q}_T$ together accounted for 86 per cent of the variance of Phases I & II ($p < 0.02$), according to the regression formula calculated from the data:

$$\text{Rate of Washin of Phases I \& II } (\Delta PaO_2/\text{sec.}) = -0.01\ (A\text{-}aDO_2) + -1.93\ (\dot{Q}_{VA}/\dot{Q}_T) + 4.03$$

Thus, the best single indicator of the rate of washin of Phases I & II was the $A\text{-}aDO_2$ ($r^2 = 0.75$, $p < 0.05$). The best combination of indicators of the rate of washin of Phases I & II were $A\text{-}aDO_2$ and $\dot{Q}_{VA}/\dot{Q}_T$ ($r = 0.86$, $p < 0.02$).

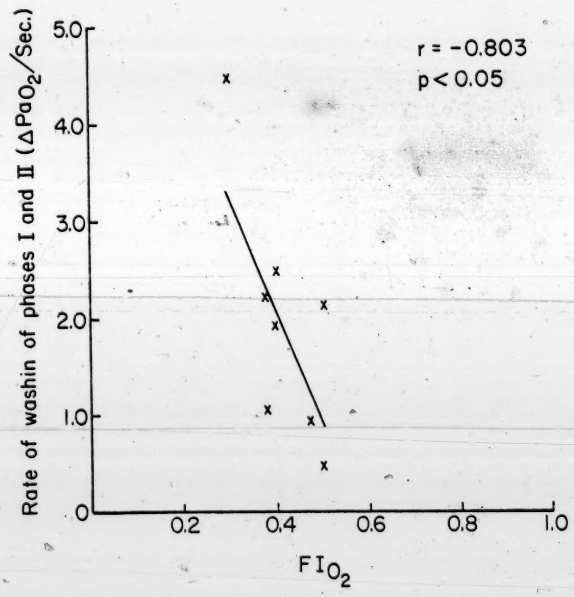

Figure 7. The relationship between starting inspired oxygen concentration (FIO_2) and the rate of washin of Phases I & II.

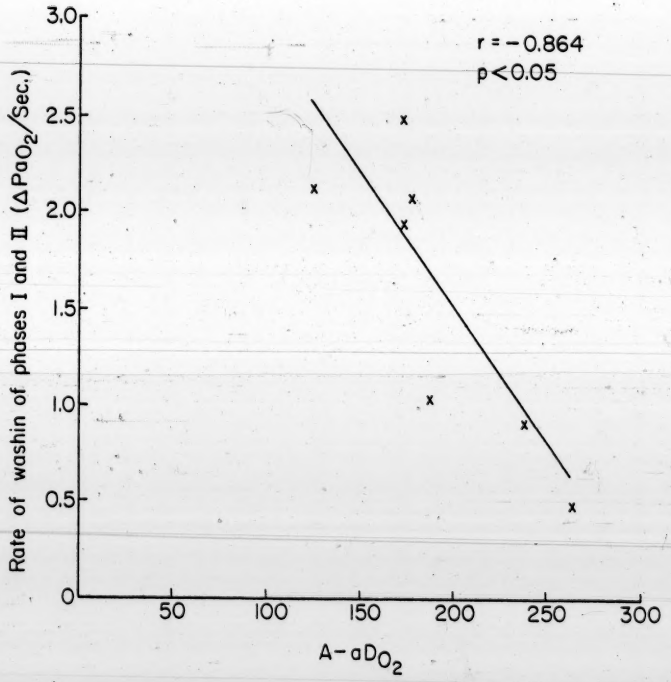

Figure 8. The relationship between starting alveolar-to-arterial oxygen tension difference ($A-aDO_2$) and the rate of washin of Phases I & II.

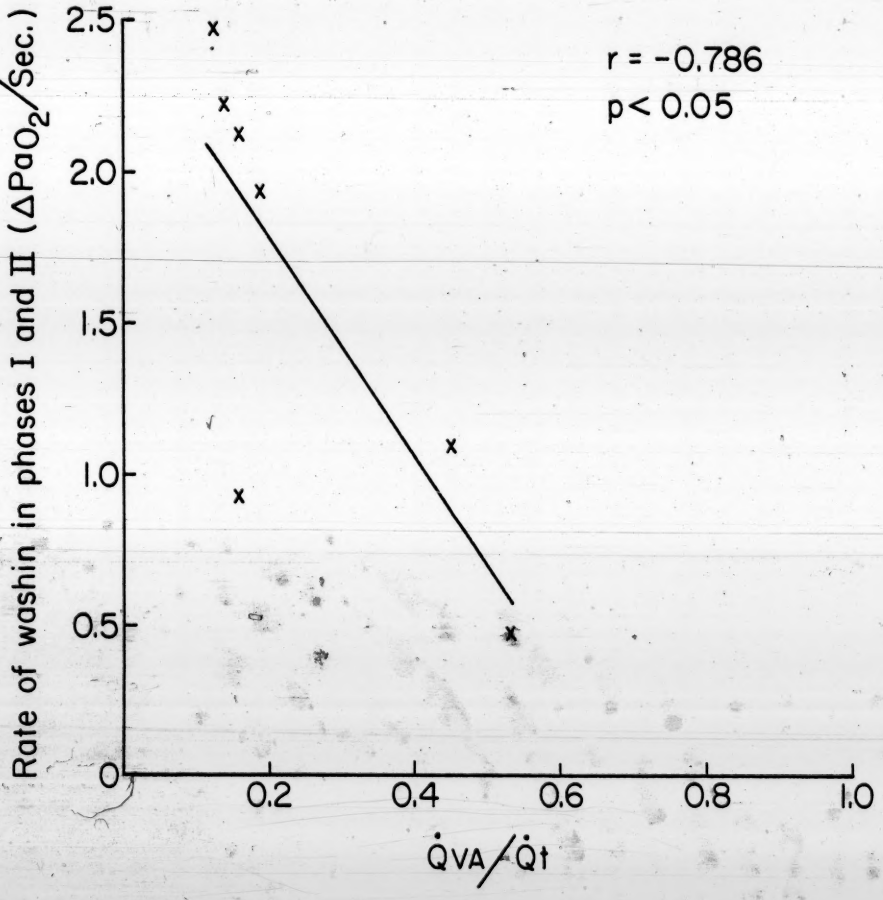

Figure 9. The relationship between the starting shunt fraction ($\dot{Q}_{VA}/\dot{Q}_T$) and the rate of washin of Phases I & II.

Table 11

Coefficients of Determination (r^2) Between Variables Thought to Affect the Rate of Washin and the Rate of Washin of Phases I & II, II, and III.

Phase	FIO_2	$A\text{-}aDO_2$	$\dot{Q}_{VA}/\dot{Q}_T$	C.I.	V_D/V_T	$\dot{V}_{ALV.}/m^2$	FRC	C_{LT}
I & II[a]	0.645	0.746	0.617	0.097	0.053	0.033	0.258	0.012
II	0.488	0.719	0.548	0.073	0.188	0.037	0.090	0.011
III	0.260	0.113	0.001	0.140	0.690	0.225	0.004	0.006

[a]Since the time of Phase I was less than the 30 second standard hyperinflation period, Phases I & II were combined in order to determine if the ventilator and /or circulation lag times were factors in establishing adequate oxygenation.

When variables measured prior to washin were correlated with the rate of washin of Phase II alone, A-aDO_2 was the only variable with a significant effect on Phase II (See Table 10). Subjects in whom the starting A-aDO_2 was low had faster washins during Phase II (See Figure 10). All variables measured prior to washin were correlated singly (See Table 11) and in combination with the rate of washin of Phase II. Only A-aDO_2 had a significant relationship with Phase II. A regression calculated for the A-aDO_2 and the rate of washin of Phase II, according to the regression formula was:

$$\text{Rate of Washin of Phase II } (\Delta PaO_2/\text{sec.}) = -0.016\ (A\text{-}aDO_2) + 5.31$$

$$[\ r = 0.72,\ p < 0.02]$$

When a multiple regression was calculated between the combined effects of variables measured before washin and the rate of washin of Phase II, only the combination of A-aDO_2 and FIO_2 was significant. A multiple regression calculated between A-aDO_2 and FIO_2 and the rate of washin of Phase II, according to the regression formula from data calculated for seven subjects was:

$$\text{Rate of Washin of Phase II } (\Delta PaO_2/\text{sec.}) = -0.023\ (A\text{-}aDO_2) + 7.9\ (FIO_2) + 3.158$$

$$[r = 0.84,\ p < 0.025]$$

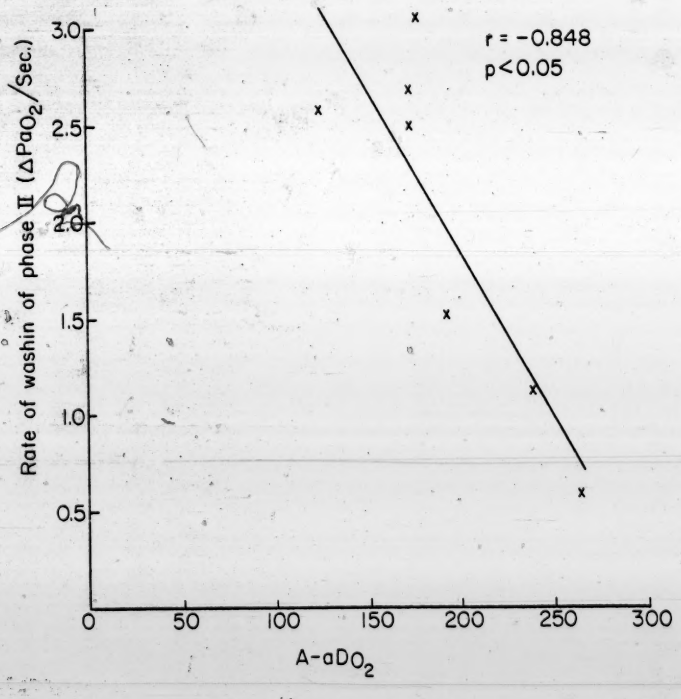

Figure 10. The relationship between the starting alveolar-to-arterial oxygen tension difference ($A\text{-}aDO_2$) and the rate of washin of Phase II.

The deadspace ratio (V_D/V_T) was negatively correlated to the rate of washin of the slow component (Phase III) (See Table 10). The smaller the deadspace ratio, the faster the rate of washin occurred during Phase III (See Figure 11). During Phase III, the deadspace ratio accounted for 69 per cent of the variance in the rate of washin of Phase III ($p < 0.05$), according to the regression formula calculated from the data of seven subjects:

$$\text{Rate of Washin of Phase III } (\Delta PaO_2/\text{sec.}) = 0.638\ (V_D/V_T) + 0.528$$

Variables measured prior to the oxygen washin were compared (See Table 12) to determine if there were correlates which could be used as pre-washin descriptors of the subjects studied. There were no statistically significant correlations between variables that could be used as predictors in the subjects studied.

Summary of Results

Eight subjects requiring ventilation for acute respiratory failure were studied over a five month period in order to identify the physiologic determinants of an optimum method of endotracheal aspiration. In order to determine the magnitude of changes of specific hemodynamic and respiratory variables

Table 12

Matrix of Correlation Coefficients (r) of Variables

Measured Prior to Oxygen Washin*

	FIO_2	A-aDO_2	$\dot{Q}_{VA}/\dot{Q}_T$	C. I.	V_D/V_T	$\dot{V}_{ALV.}/m^2$	FRC	C_{LT}
FIO_2	1.000							
A-aDO_2	0.692	1.000						
$\dot{Q}_{VA}/\dot{Q}_T$	0.173	0.598	1.000					
C. I.	-0.522	-0.134	0.662	1.000				
V_D/V_T	0.632	0.670	0.014	-0.559	1.000			
$\dot{V}_{ALV.}/m^2$	-0.696	-0.179	0.564	0.928	-0.640	1.000		
FRC	-0.522	-0.095	-0.230	-0.313	0.341	0.055	1.000	
C_{LT}	-0.014	-0.486	-0.626	0.100	-0.145	0.014	0.022	1.000

*None of the Correlation Coefficients were statistically significant at the $p < .05$ level.

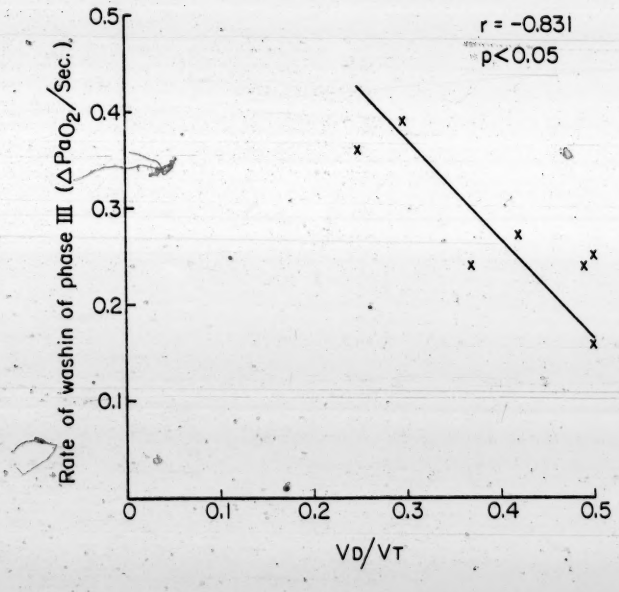

Figure 11. The relationship between the starting V_D/V_T and the rate of washin of Phase III.

which occur during and after endotracheal aspiration, data for the eight subjects from baseline and post-suction measurements were compared using paired t-tests. The only significant changes found were an increased arterial oxygen tension after suction ($p < 0.005$) and a decreased alveolar-to-arterial oxygen tension difference ($p < 0.05$). Changes in all other variables were found statistically non-significant.

In order to investigate the correlation between the magnitude of changes in hemodynamic and respiratory variables during endotracheal aspiration and their status prior to aspiration, arterial oxygen tensions, measured from serial samples drawn during the suction sequence, were compared to baseline cardio-respiratory variables. Only two cardio-respiratory variables measured were significantly correlated to the per cent change in arterial oxygen tension during the suction sequence--the per cent of oxygen washin after 30 seconds ($r = 0.799$, $p < 0.05$) and the rate of washin of Phases I and II combined ($r = 0.719$, $p < 0.05$).

In order to determine whether a standardized length of pre-oxygenation time provides adequate safety during tracheo-bronchial suction or whether a clinical index would serve as an appropriate guide to the length of time necessary to prevent hypoxemia, a five minute period of oxygen washin was performed on each subject and four phases of washin

identified--Phases I, II, III, IV. Alveolar-to-arterial oxygen tension was the single best indicator of the rate of washin of Phases I and II combined ($r^2 = 0.72$, $p < 0.016$) and of Phase II alone ($r^2 = 0.75$, $p < 0.01$). The combined effects of alveolar-to-arterial oxygen tension differences and shunt were the best indicators of Phases I and II combined ($r^2 = 0.86$, $p < 0.02$), while alveolar-to-arterial oxygen tension difference and the fraction of inspired oxygen were the best indicators of the rate of washin of Phase II alone ($r^2 = 0.84$, $p < 0.025$). The deadspace ratio was the best single indicator of the rate of washin of Phase III ($r = -0.848$, $p < 0.05$).

CHAPTER VI

DISCUSSION

Endotracheal aspiration is known to be a hazardous procedure though it is an effective means of eliminating copious secretions in patients with acute respiratory failure. The purpose of this study was to explore the physiological determinants of a clinically successful method of endotracheal aspiration in patients with acute respiratory failure. Three objectives were specifically devised to achieve this purpose: (1) determination of the magnitude of changes of specific hemodynamic and respiratory variables which occur during and after endotracheal aspiration; (2) investigation of the correlation between the magnitude of hemodynamic and respiratory changes during endotracheal aspiration and their physiological status prior to aspiration; and (3) determination of whether a standardized length of preoxygenation time provides adequate safety during tracheo-bronchial aspiration or whether a clinical index, e.g., compliance, would serve as an appropriate guide to the length of preoxygenation time necessary to prevent hypoxemia. Discussion of the results

of this study will be presented according to the objectives.

Objective 1

Determination of the magnitude of changes of specific hemodynamic and respiratory variables which occur during and after endotracheal aspiration.

Decreased arterial oxygen tension has been reported during and after endotracheal aspiration in a wide variety of subjects (Berman et al., 1968; Boba et al., 1959; Boutros, 1970; Boutros et al., 1967; Downes et al., 1961; Fell et al., 1971; Schmidt, 1966; Stephen et al., 1951; Taylor et al., 1971). Several mechanisms may be responsible for this decrease: first, dilution of the alveolar gas with air in instances where the inspired oxygen tension is greater than room air; second, apnea in patients requiring constant artificial ventilation; and, third, atelectasis resulting from the development of intra-airway negative pressures with and accompanying increase in shunt and alveolar-to-arterial oxygen tension difference.

Clinical data from the present study do not substantiate this hypothesized decrease in arterial oxygen tension. Though a wide variety of hemodynamic and respiratory variables were investigated, paired t-tests did not demonstrate significant

changes between before and after measurements except in PaO_2 and $A\text{-}aDO_2$ which were significantly improved, i.e., PaO_2 increased after suction and $A\text{-}aDO_2$ decreased post-suction. These findings are in contrast to those of Schmidt (1966) who found the expected increase in cardiac output and in stroke volume after suction as well as a decrease in PaO_2.

Although all subjects studied were ventilated on inspired oxygen concentrations above room air (See Table 2) and would have been expected, therefore, to have had lung air diluted with room air during the process of endotracheal aspiration with a resultant decrease in arterial oxygen tension, the opposite result occurred, i.e., arterial oxygen tension increased after suction. Likewise, the gradient between alveolar and arterial oxygen tensions decreased.

Secondly, each subject studied experienced a 20 second period of apnea during the time in which suctioning was performed. During this period while the lung store of oxygen was being depleted and not replaced, it was expected that arterial oxygen tension would have decreased, but the clinical data do not support this expectation.

Thirdly, it was possible that the development of intra-airway negative pressures might have resulted in atelectasis

and accompanying shunt and alveolar-to-arterial oxygen tension differences. Clinical data, however, demonstrated no significant change in lung-thorax compliance nor in functional residual capacity. Moreover, neither cardiac output nor shunt showed any significant change. These clinical measurements would have reflected the occurrence of atelectasis. Alveolar-to arterial oxygen tension difference, however, improved after endotracheal aspiration, further indicating that no atelectasis had occurred.

These findings are opposite to those of Brandstater et al. (1969) who found decreased compliance in mechanically ventilated infants after suction. They suggested that collapsed air spaces were responsible for this decreased compliance. In their study compliance was returned to normal by sustained hyperinflation after suction. Likewise, Egbert et al. (1963) demonstrated that although compliance decreased after suction, several deep inflations were sufficient to improve it. Subjects in whom they were able to remove secretions from the trachea during suction had compliance improved over baseline values.

Thus, in the present study, the standardized suction sequence used was adequate not only to prevent decreased arterial oxygen tension after suction but to improve it.

These arterial oxygen tensions were measured from blood samples drawn before the 30 seconds of hyperinflation with 100 per cent oxygen prior to suction and after the 30 seconds of hyperinflation with 100 per cent oxygen post-suction. These two periods of hyperoxygenation appear to have been sufficient to show improved oxygen tension at the end of the data collection period.

In addition, it is possible that subjects who had copious secretions blocking their airways had improved ventilation after these secretions were removed by suction. This improved ventilation may have contributed to the improved arterial oxygen tension after aspiration.

Together with improved arterial oxygen tension and improved alveolar-to-arterial oxygen tension difference, it would have been expected that a concomitant improvement in arterial oxygen tension, the oxygen saturation of both the arterial and venous blood, and the content of oxygen in both the arterial and venous blood might have occurred. That these were not significantly different may be a result of the small sample size studied. In addition, the saturation of the hemoglobin may not have been affected in that only one of the subjects studied was on the steep slope of the oxygen-hemoglobin dissociation curve (See Table 6) (Comroe et al., 1962). Thus, even though all subjects studied showed increases both

in arterial oxygen tension and in arterial oxygen saturation, the changes in arterial oxygen saturations were not great enough to be statistically significant.

Another possible outcome of endotracheal aspiration is atelectasis resulting from the development of intra-airway negative pressures. This atelectasis can be manifested by a decrease in lung-thorax compliance and by a decrease in functional residual capacity as well as by an increase in venous admixture. One common cause of increased intra-airway negative pressure is impaction of the suction catheter into the endotracheal tube. Since, in this study, the recommendations of Rosen et al. (1962) were followed so that no subject had a ratio of the external diameter of the suction catheter to the internal diameter of the endotracheal tube of greater than 0.5 (See Table 4), it is possible that no intra-airway negative pressure sufficient to cause atelectasis was created.

A number of variables which indicate the steady-state of the subjects were not expected to change after suction, i.e., arterial and mixed venous carbon dioxide tensions and carbon dioxide production and the ratio of deadspace to tidal volume. As predicted there was no significant change in these variables.

Summary of the Results of Objective 1

Determination of the magnitude of changes of specific hemodynamic and respiratory variables which occur during and after endotracheal aspiration was made through the measurement of a large number of hemodynamic and respiratory variables before and after a standardized suction sequence which included two thirty second periods of hyperinflation with 100 per cent oxygen. Before and after measurements of these variables were compared through paired t-tests with the result that the subjects studied showed improved arterial oxygen tensions and improved alveolar-to-arterial oxygen tension differences after the suction sequence. It was suggested that the two periods of hyperinflation with 100 per cent oxygen before and after the actual period of suction were sufficient to show an end net result of improved arterial oxygen tension and alveolar-to-arterial oxygen tension differences.

Objective 2

Investigation of the correlation between the magnitude of hemodynamic and respiratory changes during endotracheal aspiration and their physiological status prior to aspiration.

In order to identify a clinical measurement which would predict the change in arterial oxygen tension during suction, a number of variables were examined which were thought to affect the change in arterial oxygen tension during the suction sequence. It was hypothesized that subjects with low initial resting lung volumes (control FRC) might require less time to washin oxygen prior to endotracheal aspiration than those with large resting lung volumes. As oxygen was replaced by air during the actual suction process, those patients with small FRC's would develop decreases in arterial oxygen tension more quickly than those with large resting lung volumes. It was further hypothesized that low lung-thorax compliance, would serve as a clinical indicator of those subjects who would experience the greatest decreases in arterial oxygen tension during the suction sequence.

Clinical data did not demonstrate significant correlations between either FRC or lung-thorax compliance and the change in arterial oxygen tension during the suction sequence (See

Table 7). FRC as a per cent of the predicted value did show a positive correlation to the per cent change in arterial oxygen tension during the suction sequence even though this correlation was not statistically significant, i.e., the smaller the FRC as a per cent of the predicted FRC the lower the arterial oxygen tension was during the suction sequence in relation to its baseline value ($r = 0.628$, $p < 0.13$, $n = 7$).

From the small sample size studied ($n = 7$) it is not possible to determine if this trend would continue if a larger sample size were studied. Even though only two of the subjects studied demonstrated negative changes from baseline in arterial oxygen tensions during the suction sequence, these data support the original supposition that subjects with small resting lung volumes would decrease arterial oxygen tension more than those with large resting lung volumes. In addition, those subjects with the lowest initial resting lung volumes expressed as a percentage of the predicted volumes showed the lowest arterial oxygen tensions during the entire suction sequence.

Another possible explanation for why a statistically significant correlation was not found between the resting FRC and the change in arterial oxygen tension during the suction sequence is the sensitivity of the FRC measurement

which in the subjects studied had a mean of 1889 ± 675. Reliability measures of this method on varying concentrations of oxygen on a known volume yielded a coefficient of variation of 0.028, and in a series of duplicate determinations done under identical ventilatory conditions on ten patients requiring mechanical ventilation the second value differed from the first by 2 per cent (See Appendix A). Thus, the FRC measurement itself may not have been sensitive enough to detect relatively small differences in FRC which could affect changes in arterial oxygen tensions during the suction sequence.

The finding that there was a significant correlation between the per cent of oxygen washin after thirty seconds of hyperinflation with 100 per cent oxygen and the per cent change in arterial oxygen tension during the suction sequence was expected according to the mathematics of exponential change, i.e., the rate of change varied as the difference in values at the start and at the finish. The fact that this explanation was confirmed physiologically in the subjects studied suggest that FRC may be an important factor. Subjects who had a lower per cent washin of oxygen at thirty seconds had lower arterial oxygen tensions expressed as a per cent of their baseline values. One reason for this lower per cent of oxygen washin

at thirty seconds may be small resting FRC's in these subjects. Thus, these subjects would have smaller stores of oxygen in their lungs, which stores would be quickly depleted during the apnea concomitant with the actual suction period and which stores would be quickly diluted with air during the suction period.

The rate of washin of Phases I and II of the oxygen washin curve was also significantly correlated to the per cent change in arterial oxygen tension during the suction sequence. Since the combination of Phases I and II encompasses the first 30 seconds of the washin, these two findings coincide partially. The rate of washin of these two phases is influenced by a number of cardiovascular and respiratory variables and will be discussed under Objective 3 in this chapter.

Other variables which might affect the arterial oxygen tension change during the suction sequence were the alveolar-to-arterial oxygen tension difference and the FIO_2, the degree of shunt, and the cardiac output. None of these variables was significantly correlated with the per cent change in arterial oxygen tension during the suction sequence. It was possible that subjects with large percentages of shunt would require high levels of inspired oxygen concentration to maintain clinically acceptable

levels of arterial oxygen tension and that during the apnea and dilution of the alveolar oxygen stores with air during the suction, these subjects would demonstrate greater decreases in arterial oxygen tension than those with smaller shunts. Although in general subjects with large shunts had lower arterial oxygen tensions during the suction sequence, it is probable that the hyperinflation with 100 per cent oxygen prior to the actual period of suction was sufficient to prevent large decreases in arterial oxygen tension during the actual period of suction.

No studies have been reported in which the change in arterial oxygen tension as a result of suction has been correlated to the washin of oxygen prior to suction. Several studies have, however, used hyperinflation with 100 per cent oxygen prior to suctioning, and the results of these studies concur with those of this study.

Fell et al. (1971) reported that subjects ventilated with 100 per cent oxygen did not show decreases in arterial oxygen tension below baseline at the end of 15 seconds of suction. Some subjects showed increased PaO_2 after 15 seconds of suction, which increase was explained as due to re-expanded collapsed air spaces from the expectoration of secretions obstructing the airways. Downes et al. (1961) reported in studying apnea

that every subject who received prior hyperventilation with 100 per cent oxygen was able to maintain oxygen saturation above 95 per cent during apnea while subjects who did not receive prior hyperventilation with 100 per cent oxygen were not.

Boutros (1970) used sustained hyperinflation for 10 seconds following suctioning which resulted in significantly smaller relative decreases in PaO_2 than no hyperinflation. The absolute values of oxygen tension in subjects in this study were, however, within the non-hypoxic range.

Summary of the Discussion of the Results of Objective 2

Identification of a clinical measurement which would be associated with the change in PaO_2 during the suction sequence was made through correlating a wide range of hemodynamic and respiratory variables measured prior to the suction sequence to the per cent change in arterial oxygen tension during the suction sequence. That variable which was found to best indicate the per cent change in arterial oxygen tension was the per cent of oxygen washin at the end of the thirty seconds of hyperinflation with 100 per cent oxygen. Subjects who had lower per cent of washin of oxygen after thirty seconds had lower arterial oxygen tensions during the suction sequence. That other variables thought to affect the

per cent change in arterial oxygen tension during the suction sequence were not significantly related may be the result of the effectiveness of the hyperpreoxygenation before the actual period of suction.

These findings, therefore, reinforce those of Fell et al. (1961) and Downes et al. (1961) that hyperinflation should be used clinically prior to endotracheal aspiration in patients with acute respiratory failure.

Objective 3

Determination of whether a standardized length of preoxygenation time provides adequate safety during tracheobronchial aspiration or whether a clinical index, e.g., compliance, would serve as an appropriate guide to the length of preoxygenation time necessary to prevent hypoxia.

In order to determine whether a thirty second period of hyperinflation with 100 per cent oxygen was adequate to prevent hypoxemia during endotracheal aspiration, ventilation and circulation effects were evaluated by measuring arterial oxygen tensions during a five minute period of hyperinflation with 100 per cent oxygen at one and one half the maintenance tidal volume in order to generate an oxygen washin curve on each subject studied.

Since washin curves are usually exponential in nature, the oxygen washin curve of each subject was linearized by converting each arterial oxygen tension to its logarithm and plotting these values over time. It was found that these oxygen washin curves had four components which were divided into phases: Phase I--the initial plateau; Phase II--the fast filling component; Phase III--the slow filling component; and Phase IV--the reabsorption component.

Phase I.

Timing of the oxygen washin began with changing the FIO_2 regulator of the ventilator to hyperventilate with 100 per cent oxygen. As found by Colgan et al. (1970), after the initial changeover of the ventilator a period of circulation and system lag time occurred before the change of O_2 introduced into the ventilator affected the PaO_2 at the sampling port at the femoral artery. Two factors account for this lag time; (1) the patient's circulation time, and (2) the system's changeover time.

The ventilator requires a period of changeover before a concentration of oxygen delivered through the endotracheal tube reaches 100 per cent. The factor responsible for this changeover time is the washout time of the ventilator itself and of the dead space tubing from the ventilator to the end of the subject's endotracheal tube. This washout time is proportional to the amount of deadspace and the rate of flow of the gas. Although not specifically measured in this study, this washout time appears to be fairly constant among subjects as the same type of ventilator was used in all cases except one. In future studies it is recommended that either the same ventilator be used for all subjects or that at least the washout time of each ventilator used be measured prior to the onset of the experimental period so that consistency

can be established among ventilators on the basis of concrete data. Even better would be the use of two ventilators, one at the maintenance levels and one at 100 per cent oxygen.

Any factor which affects arterial oxygenation will also affect the patient's lag time, i.e., that time from the change in FIO_2 until a change in PaO_2 occurs at the sampling site. Thus, subjects with low cardiac outputs and/or large shunts will have longer periods before arterial oxygen tension will begin to rise.

Because Phase I encompasses both mechanical and cardio-respiratory variables, it is a difficult phase to analyse. For the purpose of this study, the ventilator variable has been assumed constant across the subjects studied and the cardio-respiratory variables assumed responsible for the differences seen between subjects. A future study might address the validity of this assumption since it is an important consideration if patients are to be hyperventilated mechanically with 100 per cent oxygen prior to suction.

Phase II and Phase III.

All subjects studied exhibited both Phase II and Phase III, indicating that the lungs of these subjects behaved as if composed of two compartments ventilating at different exchange rates--a fast exchange compartment (Phase II) and a slow exchange compartment (Phase III). These findings are in agreement with those of Colgan et al. (1970) who found that eighty-eight per cent of the lung volume ventilated faster than a smaller compartment which ventilated at a slower rate.

Since the slow ventilating compartment contributes little to the rise in arterial oxygen tension during the thirty seconds of hyperinflation with 100 per cent oxygen prior to the actual suctioning, it is the fast exchange compartment, of Phase II, which is of most concern in this study.

Phase IV.

Observed in only two subjects, Phase IV represented a decrease in arterial oxygen tension during the latter portion of the five minute oxygen washin curve. Ventilation with 100 per cent oxygen for 20 minutes had been found to cause increased PaO_2, decreased FRC, and increased shunt (Suter, Fairley, & Schlobohm, 1975). The causative mechanism is thought to be alteration of the measured intrapulmonary

shunt by three different mechanisms: (1) elimination of the effects of diffusion hindrance and ventilation-perfusion inequalities; (2) formation of resorption atelectasis which resulted in loss of resting lung volume and increased shunt; and (3) redistribution of the regional pulmonary blood flow by vascular autoregulatory mechanisms which influence the changes in shunt.

The one subject who demonstrated the most pronounced Phase IV during 5 minutes of ventilation with 100 per cent oxygen had demonstrated a decrease in PaO_2 from maximum washin at least one other time during ventilation with 100 per cent oxygen for routine clinical measurements. At the end of Phase IV, however, the PaO_2 was still increased from the baseline value and therefore in agreement with the single measurement point of Suter et al. (1975). This subject was being routinely maintained on an inspired oxygen concentration of 50 per cent. It is possible that this ventilation with a high FIO_2 produced high alveolar oxygen tensions in normally ventilated or slightly underventilated alveoli and increased $P\bar{v}O_2$ and that pulmonary arterioles and capillaries perfusing these areas were maximally dilated. If full dilation already existed in the ventilated portions, further dilation only occurred in atelectatic or grossly underventilated segments

of the lung. Consequently, ventilation with 100 per cent oxygen resulted in an increase of venous admixture in those cases where atelectatic areas were present during ventilation with lower oxygen concentrations and when additional atelectasis is produced (Suter et al., 1975).

Clinical Indicators of Washin

In order to identify a clinical measurement which would predict the rate of washin to be expected in a particular subject, a number of variables were examined which were thought to influence the washin of gases. These variables were examined in relation to the rates of washin of Phases I, II, and III (See Table 10). Phases I and II were combined because Phase I was not present in all subjects studied and because when present Phase II encompassed only part of the standard thirty seconds of hyperventilation with 100 per cent oxygen.

Phases I and II. Three variables were negatively correlated with the rates of washin of Phases I & II. The lower the starting inspired oxygen concentration, the lower the starting alveolar-to-arterial oxygen tension difference, and the lower the starting shunt fraction, the faster the oxygen washin of Phases I & II combined occurred (See Table 10).

As demonstrated by the oxygen washin curves generated on the subjects in this study and by Colgan et al. (1970),

oxygen washin occurs exponentially. Thus, the greater the FIO_2 required by a subject to maintain a clinically acceptable arterial oxygen tension, the higher he is on the linear portion of the oxygen washin curve (See Figure 5). Increasing the FIO_2 to 100 per cent, therefore, quickly moves him out of the linear portion of the curve so that the rate of washin when calculated for Phases I and II combined is slower than that of subjects whose maintenance FIO_2 is close to room air and who therefore have a longer portion of their washin on the linear portion of the curve.

In addition, subjects requiring relatively high maintenance FIO_2 in order to maintain clinically acceptable levels of arterial oxygen tension were those with the highest alveolar-to-arterial oxygen tension differences, indicating that these subjects had problems of arterial oxygenation. Though shunt measurements were not significantly correlated to the maintenance FIO_2, there was a trend that those subjects requiring higher FIO_2 had larger shunt fractions. Also, though not significantly correlated, subjects who required high maintenance FIO_2 had larger ratics of deadspace which may also have contributed to their decreased arterial oxygenation (See Table 10). Thus, the washin of oxygen as measured by PaO_2 was slower in these subjects.

Both alveolar-to-arterial oxygen tension difference and

the shunt fraction were significantly correlated to the rate of washin of Phases I & II combined even though these two variables were not significantly correlated to each other. Thus, each was a predictor of the rate of washin of Phases I and II combined. Multiple regression showed that the alveolar-to-arterial oxygen tension difference was the best predictor of this rate of washin. Since shunt deals with content differences and $A\text{-}aDO_2$ is really a measurement amplifier for content differences at high FIO_2 values, this is not surprising.

Since the shunt fraction was the only other variable measured which was significantly correlated with the rate of washin of oxygen, it is the most likely explanation for the disruption of the ventilatory exchange found in these subjects. In fact, when the effects of $\dot{Q}_{VA}/\dot{Q}_T$ and $A\text{-}aDO_2$ were combined, the ability to predict the variance of washin of Phase I & II was improved, accounting for 86 per cent of the variance ($p<0.02$). Thus, knowing both of these values, increases the ability to predict the rate of washin, which is greater than the per cent of prediction of either value alone.

The speed and equality of the distribution of inspired air may have also been a factor, but data from this study cannot be used either to prove or disprove this supposition. It was

expected that a factor affecting the speed of the distribution of the inspired air would be the functional residual capacity in that subjects who had large functional residual capacities would have large stores of lung gas which would have to be washed out and therefore would demonstrate slower washin rates of oxygen. Likewise, those subjects with small FRC's, most likely those with some degree of atelectasis and thus increased shunt fractions and increased alveolar-to-arterial oxygen tension differences, would washin more quickly. It was expected also that lung-thorax compliance would be decreased in subjects with atelectasis and thus would be a predictor of the rate of washin. It may be, however, that the problems of exchange in these subjects prevented the more rapid washin of oxygen.

These results are in opposition to those of Colgan et al. (1970) who found that atelectasis expedited alveolar washin of oxygen, presumably by reducing the functional residual capacity. The subjects used, however, were ventilating spontaneously and demonstrated increased respiratory rates secondary to the induced atelectasis. Subjects in the present study were on volume-controlled ventilators and did not have suddenly induced atelectasis, which presumably would have increased the respiratory rate and thus facilitated oxygen washin.

Eger (1974) reported that the washin of anesthetic agents depended on the relationship between alveolar ventilation and functional residual capacity. The larger the ratio of these two, the faster the rate of rise. Thus, in the Colgan study, increased respiratory rate may have increased alveolar ventilation in the atelectatic subjects causing an increased washin of oxygen.

In the present study there was no correlation between alveolar ventilation and the rate of washin of Phases I & II (See Table 9), indicating that alveolar ventilation was not a factor in these subjects, nor was there a correlation between that ratio of alveolar ventilation to FRC and the rate of washin, indicating that other factors must be operative than those affecting the rate of alveolar washin. Another difference between the Colgan study, Eger's data, and the present study is that in both of the former, normal subjects were used and in the present one patients who had varying degrees of lung pathophysiology and who had been maintained on various levels of inspired oxygen concentrations were used. Thus, in the present study A-aDO_2 was the best predictor of the rate of washin.

Phase II. Only alveolar-to-arterial oxygen tension difference was significantly correlated to the rate of the washin of

oxygen of Phase II alone. It was, therefore, the best single predictor of the rate of washin of this phase, i.e., the rapid washin phase. Although the concentration of inspired oxygen and the fraction of shunt were not significantly correlated to the rate of washin of this phase as they were to the rate of washin of Phases I & II combined, they were negatively correlated to it, indicating that the same mechanisms were responsible for the rate of washin of Phase II as were involved for Phases I & II combined. The combined effects of $A\text{-}aDO_2$ and FIO_2, however, were the best predictors of the rate of washin of Phase II, accounting for 84 per cent of the variance ($p < 0.025$).

Phase III. The only variable measured which was significantly correlated to the rate of washin of Phase III was the deadspace ratio, that is, the smaller the V_D/V_T the faster the rate of washin occurred. In all subjects studied the onset of Phase III began after the initial 30 seconds of washin, and thus it contributed little to the hyperpreoxygenation prior to suction. Subjects hyperpreoxygenated for greater than thirty seconds might, however, move into the slow washin phase.

Because all the subjects studied had shunts greater than normal and functional residual capacities smaller than their predicted values, it is possible that each had some degree of atelectasis. In addition, all subjects studied were being

maintained on levels of FIO_2 above room air. Thus, after completion of the fast washin phase, the alveoli may have been dilated in the atelectatic areas with the result that those subjects with the largest atelectatic areas who therefore had the largest deadspace ratios also had the slowest rates of washin.

Summary of the Discussion of the Results of Objective 3

Determination of whether a standardized length of preoxygenation time provides adequate safety during tracheobronchial aspiration or whether a clinical index, e.g., compliance, would serve as an appropriate guide to the length of preoxygenation time necessary to prevent hypoxia was made through examining the factors which affect the washin of oxygen. It has been demonstrated that the rate of washin of oxygen is the best predictor in the subjects studied of the change in arterial oxygen tension during the suction sequence.

Oxygen washin occurs exponentially and oxygen washin curves demonstrated four phases: Phase I--the initial plateau; Phase II--the fast filling component; Phase III-the slow filling component; and Phase IV--the reabsorption component. Since the standardized length of preoxygenation time occured during Phases I & II, factors predicting the rate of washin of these phases were identified as the baseline FIO_2, $A\text{-}aDO_2$, and

$\dot{Q}_{VA}/\dot{Q}_T$. The $A\text{-}aDO_2$ was the best single predictor of the rate of washin of this combined phase, and the $A\text{-}aDO_2$ and $\dot{Q}_{VA}/\dot{Q}_T$ were the best combined predictors.

Thus, in the eight subjects studied, a standardized length of preoxygenation time was adequate to provide safety during endotracheal aspiration. Since the rate of washin during this standardized preoxygenation period was statistically significantly correlated to the per cent change in arterial oxygen tension during the suction sequence, it is clinically useful to estimate the rate at which washin will occur. The alveolar-to-arterial oxygen tension difference was shown in this study to be the strongest single indicator of this rate of washin. Shunt was also a statistically significant indicator. Thus, clinically the alveolar-to-arterial oxygen tension difference and the shunt can be used to predict the rate of washin during preoxygenation, i.e., the greater the $A\text{-}aDO_2$ and the greater the shunt, the slower the washin will occur.

CHAPTER VII

SUMMARY

Eight patients requiring ventilation for acute respiratory failure were studied to identify the physiological determinants of a clinically successful method of endotrachael aspiration in patients with acute respiratory failure by: (1) determination of the magnitude of changes of specific hemodynamic and respiratory variables which occur during and after endotracheal aspiration; (2) investigation of the correlation between the magnitude of hemodynamic and respiratory changes during endotracheal aspiration and their physiological status prior to aspiration; and (3) determination of whether a standardized length of preoxygenation time provides adequate safety during endotracheal aspiration or whether a clinical index, e.g., compliance, would serve as an appropriate guide to the length of preoxygenation time necessary to prevent hypoxemia.

A standardized suction sequence was used in which each subject received thirty seconds of hyperinflation with one hundred per cent oxygen through a volume-controlled ventilator prior to suction, a twenty second period of suction, and a thirty

second period of hyperinflation with one hundred per cent oxygen before returning to baseline ventilation. In addition, a five minute period of oxygen washin was performed on each subject approximately one hour prior to institution of the suction sequence.

Arterial oxygen tension (PaO_2) increased from 85 $\pm$ 13 (mean $\pm$ S.E.) from before institution of the suction sequence to 96 $\pm$ 14 (mean $\pm$ S.E.) after return to baseline ventilation. Alveolar-to-arterial oxygen tension difference ($A\text{-}aDO_2$) decreased from 191 $\pm$ 18 (mean $\pm$ S.E.) before suction to 183 $\pm$ 17 (mean $\pm$ S.E.) after suction. Since these subjects were apparently in a steady state during the measurements as evidenced by no change in the rate of CO_2 production, the standardized suction sequence in these subjects was adequate not only to prevent an overall decrease in arterial oxygen tension but to provide a net result of improved arterial oxygenation through decrease in the $A\text{-}aDO_2$.

Identification of a clinical measurement which would predict the change in PaO_2 during the suction sequence was made through correlating a wide range of hemodynamic and respiratory variables measured prior to the suction sequence to the per cent change in arterial oxygen tension during the suction sequence. That variable which was found to best predict the per cent change in arterial oxygen tension was the per cent of oxygen

washin at the end of thirty seconds of hyperinflation with 100 per cent oxygen ($r = 0.799$; $p<0.05$) and the rate of washin ($r = 0.719$; $p<0.05$). That other variables thought to affect the per cent change in arterial oxygen tension during the suction sequence were not significant predictors may be the result of the effectiveness of the hyperpreoxygenation before the actual period of aspiration.

Determination of whether a standardized length of preoxygenation time provides adequate safety during endotracheal aspiration or whether a clinical index, e.g., compliance, would serve as an appropriate guide to the length of preoxygenation time necessary to prevent hypoxia was made through examining the factors which affect the washin of oxygen. Oxygen washin occurs exponentially, and oxygen washin curves in the subjects studied demonstrated four phases: Phase I--the initial plateau; Phase II--the fast filling component; Phase III--the slow filling component; and Phase IV--the reabsorption component.

Since the standardized length of preoxygenation time occurred during Phases I and II, factors predicting the rate of washin of these phases were identified as the baseline fraction of inspired oxygen (FIO_2) ($r = -0.803$; $p< 0.05$), the $A\text{-}aDO_2$ ($r = -0.964$; $p <0.05$), and the shunt fraction ($\dot{Q}_{VA}/\dot{Q}_T$)

($r = -0.786$; $p < 0.05$). $A\text{-}aDO_2$ was the single best predictor of the rate of washin of Phases I and II combined accounting for 72 per cent of the variance ($p < 0.016$) and of the rate of washin of Phase II alone, accounting for 75 per cent of the variance ($p < 0.01$). The combined effects of $A\text{-}aDO_2$ and $\dot{Q}_{VA}/\dot{Q}_T$ were the best predictors of the rate of washin of Phases I & II, accounting for 86 per cent of the variance ($p < 0.02$), while $A\text{-}aDO_2$ and FIO_2 were the best predictors of the rate of washin of Phase II alone, accounting for 84 per cent of the variance ($p < 0.025$). The deadspace ratio (V_D/V_T) was the best single predictor of the rate of washin of Phase III ($r = -0.848$; $p < 0.05$).

Thus, clinically the rate of washin of oxygen can be predicted in an individual patient through use of an easily measurable variable, the alveolar-to-arterial oxygen tension difference, and with even greater accuracy by using the shunt fraction ($\dot{Q}_{VA}/\dot{Q}_T$) in combination with the $A\text{-}aDO_2$. The clinician who must suction mechanically ventilated patients in whom arterial oxygen tension is low can predict that those subjects who have large $A\text{-}aDO_2$ and large $\dot{Q}_{VA}/\dot{Q}_T$ will need longer periods of hyperinflation with 100% oxygen in order to raise their arterial oxygen tensions to clinically acceptable levels prior to suction than those with low $A\text{-}aDO_2$ and $\dot{Q}_{VA}/\dot{Q}_T$.

FOOTNOTES

[1]Arterial oxygen tension.

[2]Nasal-tracheal.

[3]Arterial blood gases.

[4]Quotation from the Progress Notes of a patient at San Francisco General Hospital, 1974.

[5]Unpublished material of R. Elms, University of California, San Francisco, 1973.

REFERENCES

Abdellah, F. G. Overview of nursing research. 1955-1968. Part I. Nursing Research, January-February 1970, 19(1), 6-17.

Adair, G. S. The oxygen dissociation curve of hemoglobin. Journal of Biological Chemistry, 1925, 63, 529-545.

Adams, A. P., Morgan-Hughes, J. O., & Sykes, M. K. pH and blood-gas analysis methods of measurement and sources of error using electrode systems. Part I. Anaesthesia, October 1967, 22, 575-597.

Bates, D. V., Macklem, P. T., & Christie, R. V. Respiratory function in disease (2nd ed.). Philadelphia: Saunders, 1971.

Beland, I. L. Clinical nursing: pathophysiological and psychosocial approaches. New York: McMillan, 1970.

Benedixen, H. H., Hedley-Whyte, J., Chir, B., & Laver, M. B. Impaired oxygenation in surgical patients during general anesthesia with controlled ventilation. A concept of atelectasis. New England Journal of Medicine, November 7, 1963, 269, 991-996.

Bergman, N. A. Distribution of inspired gas during anesthesia and artificial ventilation. Journal of Applied Physiology, 1963, 18, 1085-1089.

Berman, I. R., & Stahl, W. M. Prevention of hypoxic complications during endotracheal suctioning. Surgery, 1968, 63, 568-587.

Boba, A., Concotti, J. J., Piazza, T. E., & Landmesser, C. M. The effects of apnea, endotracheal suction, and oxygen insufflation in anesthetized patients. Journal of Laboratory and Clinical Medicine, 1959, 53, 680-685.

Boutros, A. R., & Weiser, M. R. Arterial blood oxygenation during thoracotomy using 70 per cent nitrous oxide in oxygen. Anesthesiology, 1967, 28, 705-710.

Boutros, A. R. Arterial blood oxygenation during and after endotracheal suctioning in the apneic patient. Anesthesiology, February 1970, 32, 114-118.

Bradley, A. F., Stupfel, M., & Severinghaus, J. W. Effect of temperature on P_{CO2} and P_{O2} of blood in vitro. Journal of Applied Physiology, September 1956, 9, 201-204.

Brandstater, B., & Muallem, M. Atelectasis following tracheal suction in infants. Anesthesiology, 1969, 31, 468-473.

Briscoe, W. A., Cree, E. M., Filler, J., Houssay, H. E. J., & Cournand, A. Lung volume, alveolar ventilation and perfusion interrelationships in chronic pulmonary emphysema. Journal of Applied Physiology, 1960, 15, 785.

Brunner, L. S., Emmerson, C. P., Ferguson, L. K., & Suddarth, D. M. Textbook of medical-surgical nursing. Philadelphia: Lippincott, 1970.

Campbell, D. T., & Stanley, J. C. Experimental and quasi-experimental designs for research. Chicago: Rand McNally, 1963.

Cardiac arrest during therapeutic tracheal suction. Anesthesia and Analgesia-Current Researches, November-December, 1960, 39, 568-569.

Clark, L. C., Wolf, R., Granger, D., & Taylor, Z. Continuous recording of blood oxygen tensions by polygraphy. Journal of Applied Physiology, 1953, 6, 189.

Clement, J., van de Woestijne, K. P., & Pardaens, J. A general theory of respiratory mechanics applied to forced expiration. Respiratory Physiology, October 1970, 19(1), 60-79.

Colgan, F. J., & Fanning, G. L. Atelectasis: effect on distribution of ventilation and perfusion. Anesthesiology, May 1970, 32, 433-439.

Colgan, F. J., & Mahoney, P. D. The effects of major surgery on cardiac output and shunting. Anesthesiology, September 1969, 31, 213-221.

Comroe, J. H., Forster, R. E., Dubois, A. B., Briscoe, W. A., & Carlson, E. The lung, clinical physiology and pulmonary function tests (2nd ed.). Chicago: Yearbook, 1962.

Cotes, J. E. Lung function. Oxford: Blackwell, 1968.

Dale, W. A. Cardiac arrest. Annals of Surgery, March 1952, 135, 376-393.

Downes, J. J., Wilson, J. F., & Goodson, D. Apnea, suction, and hyperinflation: effect on arterial oxygen saturation. Anesthesiology, January-February 1961, 22, 29-33.

Egbert, L. D., Laver, M. B., & Benedixen, H. H. Intermittent deep breaths and compliance during anesthesia in man. Anesthesiology, January-February 1963, 24, 57-60.

Eger, E. I., II. Anesthetic uptake and action. Baltimore: Williams and Wilkins, 1974.

Eldridge, R., & Fretwell, L. K. Change in oxygen tension of shed blood at various temperatures. Journal of Applied Physiology, 1965, 20, 790-792.

Fairley, H. B., Intensive respiratory care. In H. Wolltian & C. P. Larson (Eds.), Anesthesiology. Philidelphia: Lippincott, 1976.

Fell, T., & Cheney, F. W. Prevention of hypoxia during endotracheal suction. Annals of Surgery, 1971, 174, 24-28.

Ferris, B. G., & Pollard, D. S. Effect of deep and quiet breathing on pulmonary compliance in man. Journal of Clinical Investigation, 1960, 39, 143-149.

Finley, T. H. The determination of uneven pulmonary blood flow from the arterial oxygen tension during nitrogen washout. Journal of Clinical Investigation, 1961, 40, 1727.

Guyton, A. C., Jones, E. E., & Coleman, T. G. Circulation physiology: cardiac output and its regulation. (2nd ed.). Philadelphia: Saunders, 1973.

Hedley-Whyte, J., & Laver, M. B. O_2 solubility in blood and temperature correction factors for P_{O_2}. Journal of Applied Physiology, 1964, 19, 901-906.

Hewlett, A. M., Hulands, G. H., Nunn, J. F., & Minty, K. B. Functional residual capacity during anaesthesia. British Journal of Anaesthesia, 1974, 46, 479-503.

Hulands, G. H., Greene, R., Iliff, L. D., & Nunn, J. F. Influence of anaesthesia on the regional distribution of perfusion and ventilation in the lung. Clinical Science, 1970, 38, 451-460.

Jacquette, G. To reduce hazards of tracheal suctioning. American Journal of Nursing, 1971, 71, 2362-2364.

Kaneko, K., Milic-Emili, J., Dolovich, M. B., Dawson, A., & Bates, D. V. Regional distribution of ventilation and perfusion as a function of body position. Journal of Applied Physiology, 1966, 21, 767-777.

Kelman, G. R. Digital computer subroutine for the conversion of oxygen tension into saturation. Journal of Applied Physiology, 1966, 21, 1375-1376.

Kelman, G. R., & Nunn, J. F. Nomograms for correction of blood P_{O_2}, P_{CO_2}, pH, and base excess for time and temperature. Journal of Applied Physiology, 1966, 21, 1484-1490.

Kerlinger, F. N. Foundations of behavioral research. (2nd ed.). New York: Holt, Rinehart, & Winston, 1973.

Larson, C. P., & Severinghaus, J. W. Postural variations in dead space and CO_2 gradients breathing air and O_2. Journal of Applied Physiology, 1962, 17, 417-420.

Laws, A. K. Effects of induction of anesthesia and muscle paralysis on functional residual capacity of the lungs. Canadian Anaesthetist's Society Journal, July 1968, 15, 325-331.

Levin, R. M., Seleny, F. L., Joshi, C. W., & Streczyn, M. V. The significance of transpulmonary pressure changes in children anaesthetized for cardiac surgery--analysis of respiratory mechanics. Canadian Anaesthetist's Society Journal, July 1972, 19, 381-398.

Mansell, A., Bryan, A. G., & Levinson, H. Airway closure in children. Clinical Research, 1971, 18, 803.

Marshall, B. E., Teichner, R. L., Kallos, T., Sugerman, H. J., Wyche, M. Q., Jr., & Tantum, K. R. Effects of posture and exercise on the pulmonary extravascular water volume in man. Journal of Applied Physiology, 1971, 31, 375-379.

Marx, G. F., Steen, S. N., Arkins, R. E., Foster, E. S., Joffee, S., Kepes, E. R., & Schapira, M. Endotracheal suction and death. New York State Journal of Medicine, February 15, 1968, 68, 565-566.

Needham, C. D., Rogan, M. C., & McDonald, I. Normal standards for lung volumes, intrapulmonary gas-mixing, and maximum breathing capacity. Thorax, 1954, 9, 313-325.

Nunn, J. F., Bergman, N. A., Coleman, A. J., & Casselle, D. C. Evaluation of the servomex paramagnetic analyzer. British Journal of Anaesthesia, 1964, 36, 666-673.

Nunn, J. F., Bergman, N. A., Bunatyan, A., & Coleman, A. J. Temperature coefficients for P_{CO_2} and P_{O_2} of blood in vitro. Journal of Applied Physiology, 1965, 20, 23-26.

Nunn, J. F. Applied respiratory physiology with special reference to anaesthesia. London: Butterworths, 1969.

Otis, A. B. Quantitative relationships in steady-state gas exchange. In W. O. Fenn & H. Rahn (Eds.), Handbook of physiology, Section 3: Respiration (Vol. 1). Washington: American Physiological Society, 1964.

Rattenborg, C. C., & Holaday, D. A. Mechanisms affecting ventilation and perfusion of the lungs during anesthesia. In D. A. Holaday (Ed.), Lung Disease. Philadelphia: Davis, 1967.

Rosen, M., & Hillard, E. K. The use of suction in clinical medicine. British Journal of Anesthesiology, 1960, 32, 486-504.

Rosen, M., & Hillard, E. K. The effects of negative pressure during tracheal suction. Anesthesia and Analgesia-Current Researches, January-February 1962, 41, 50-57.

Roughton, F. J. W. Transport of oxygen and carbon dioxide. In W. O. Fenn & H. Rahn (Eds.), Handbook of physiology, Section 3: Respiration (Vol. 1). Washington: American Physiological Society, 1964.

Saklad, M., & Paliotta, J. Trans-endotracheal tube suction in the stimulated breathing patient. Anesthesiology, 1967, 28, 652-660.

Schmidt, K. The effect of endotracheal toilet on circulation and on arterial and venous blood gas concentrations. Der Anesthesist, 1966, 15, 130-132.

Schumacker, H. B., & Hampton, L. J. Sudden death occuring immediately after operation in patients with cardiac disease with particular reference to the role of aspiration through the endotracheal tube and extubation. Journal of Thoracic Surgery, 1951, 21, 48-56.

Secor, J. Patient care in respiratory problems. Philadelphia: Saunders, 1969.

Segal, S. Endobronchial pressure as an aid to tracheo-bronchial aspiration, Pediatrics, 1965, 35, 305-312.

Severinghaus, J. W. Blood gas concentrations. In W. D. Fenn & H. Rahn (Eds.), Handbook of physiology, Section 3: Respiration (Vol. 2). Washington: American Physiological Society, 1965.

Shafer, K. N., Sawyer, J. R., McCluskey, A. M., Beck, E. L., & Phipps, W. J. Medical-surgical nursing. St. Louis: Mosby, 1971.

Shapiro, B. A. Clinical application of blood gases. Chicago: Yearbook, 1973.

Shim, C., Fine, N., Fernandex, R., & Williams, M. H. Cardiac arrhythmias resulting from tracheal suctioning. Annals of Internal Medicine, 1969, 71, 1149-1153.

Staub, N. C. Alveolar-arterial oxygen tension gradient due to diffusion. Journal of Applied Physiology, 1963, 18, 673-680.

Stephen, C. R., Slater, H. M., Johnson, A. L., & Sekely, P. The oximeter--a technical aid for the anesthesiologist. Anesthesiology, September 1951, 12, 541-555.

Suter, P. M., & Schlobohm, R. M. Determination of functional residual capacity during mechanical ventilation. Anesthesiology, December 1974, 41, 605-607.

Suter, P. M., Fairley, H. B., & Schlobohm, R. M. Shunt, lung volume and perfusion during short periods of ventilation with oxygen. Anesthesiology, December 1975, 43, 629-639.

Suter, P. M., Lindauer, J. M., Fairley, H. B., & Schlobohm, R. M. Errors in data derived from pulmonary artery blood gas values, Critical Care Medicine, 1975, 3(5), 175-181.

Swyer, P. R., Reiman, R. C., & Wright, J. J. Ventilation and ventilatory mechanics in the newborn. Journal of Pediatrics, 1960, 56, 612.

Taylor, P. A., & Waters, H. R. Arterial oxygen tensions following endotracheal suction on IPPV. Anesthesia, July 1971, 26, 289-293.

Urban, B. J., & Weitzner, S. W. Avoidance of hypoxemia during endotracheal suctioning. Anesthesiology, 1969, 31, 473-475.

Wade, J. F. Respiratory nursing care. Physiology and technique. St. Louis: Mosby, 1973.

Wang, C. S., & Josenhaus, W. T. Contribution of diaphragmatic abdominal displacement to ventilation in supine man. Journal of Applied Physiology, 1971, 31, 576-580.

West, J. B. Respiratory physiology. Baltimore: Williams & Wilkins, 1974.

APPENDIX A

MEASUREMENT OF FUNCTIONAL RESIDUAL CAPACITY BY THE HELIUM DILUTION METHOD DURING MECHANICAL VENTILATION

Functional residual capacity (FRC) was measured using a modification of Law's technique (1968) by Suter and Schlobohm (1974). FRC was calculated by the formula:

$$FRC = \frac{He_1}{He_2} \times V_1 - V_2$$

where He_1 = initial helium concentration

He_2 = final helium concentration

V_1 = initial spirometer volume + apparatus deadspace

V_2 = final spirometer volume + apparatus deadspace

Method

FRC was determined while the patients were ventilated with the tidal volume and frequency on which they were being maintained and with positive end expiratory pressure (PEEP) if so indicated by routine care. The patient was not disconnected from the ventilator during the measurement but was turned into the circuit through two valves. Inspired oxygen concentration was maintained above that level necessary for maintenance.

The circuit (Figure 12) included a 6 liter spirometer (Warren Collins), circulation motor, CO_2 absorber, disposable bacterial filter (Ohio), helium meter (Godart catharometer), oxygen analyzer (Beckman E-2), and a "bag-in-box" device. The "bag-in-box" consister of a 1.8 liter self-inflating rubber resuscitation bag (Air-viva, CIG Australia) within a 5 liter glass bottle with two openings--one through which the bag was connected to the FRC circuit and the other through which the space surrounding the bag was connected to the ventilator. Through a series of valves, there was a unidirectional flow of gas around the circuit in the following order: the self-inflating bag was filled from the spirometer (during expiration), the gas mixture then entered the subject's lungs, the expired gas passed through the bacterial filter and CO_2 absorber and returned to the spirometer. A helium analyzer was in a parallel circuit to the main circuit, and the gas sampled was returned to the circuit after analysis.

If PEEP was used, an Emerson PEEP Assembly was included in the expiratory part of the circuit. This arrangement allowed for measurements at PEEP, whereby only a small segment of the circuit was under continuous positive pressure.

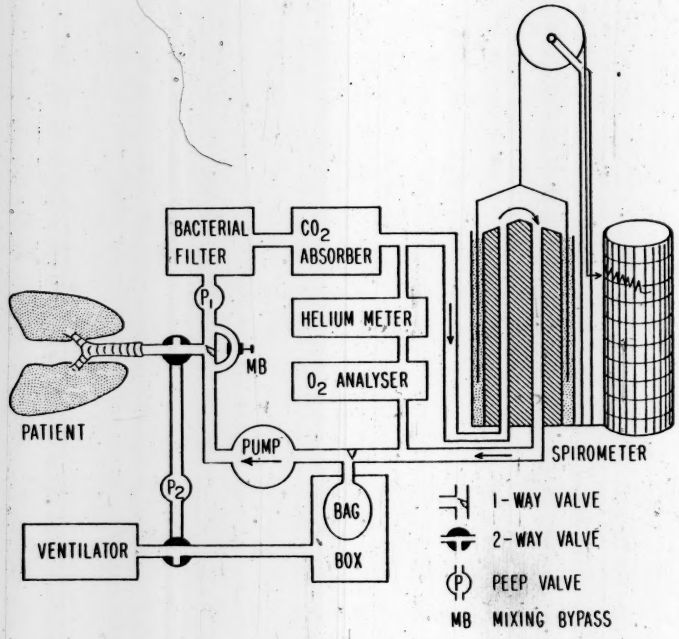

Figure 12. Circuit for FRC determinations.
(Reprinted from Suter et al., 1975)

Measurement. The circuit was filled with the helium-oxygen-nitrogen mixture, resulting in a helium concentration of 5-7 per cent. Because no oxygen was added during the measurement, the beginning oxygen concentration was set approximately ten per cent higher than the value used in ventilating the patient's lungs prior to the FRC determination. The gases were mixed in the circuit using the circulation motor and several deflations of the bag. At end-expiration the subject's connection was changed from the ventilator to the closed FRC circuit by simultaneous rotation of both two-way valves. The gas mixture in the circuit then equilibrated with the lung volume. Equilibration could be recognized by a slowly increasing helium concentration due to oxygen consumption from the circuit. During this equilibration period, which lasted 2-7 minutes, the patient's ventilator drove the "bag-in-box," thus assuring ventilatory patterns similar to those of the pre-test period. At termination, direct patient contact with the ventilator was re-established by reversing both two-way valves to their original positions at end-expiration.

Catharometer and spirometer readings were taken before turning the subject into the closed circuit and after turning him out of the circuit. FRC determinations were corrected for "turn in" or "turn out" errors, i.e., not turning the patient

into the circuit or out of the circuit exactly at end-expiration, by adding or subtracting the appropriate volume above or below end-expiration (Hewlett, Hulands, Nunn & Minty, 1974).

Validity and Reliability

Catharometer. The thermal conductivity of the spirometer gas is a satisfactory means of observing changes in the helium concentration. The response of the catharometer is directly proportional to the helium concentration. It is not necessary, therefore, to convert the reading of the meter into helium concentrations. The meter is read to one-thousandth of full scale deflection with the aid of a mirror scale. As catharometers are non-specific gas analysers, they will only indicate changes in the helium concentration if the concentrations of other gases are held constant.

The linearity of the system as a whole may be impaired by the non-linearity in the response of the catharometer. An error in the helium reading of only one-thousandth of full scale can introduce an error in the FRC of approximately three per cent. The linearity of the catharometer was checked, therefore, according to the method of Cotes (1968) and Hewlett et al. (1974), by adding serial increments of air to the circuit, which had been previously primed with helium, and recording the catharometer readings. The volume of air added was then plotted against the

reciprocal of the helium reading (Hewlett et al., 1974). (See Figure 13).

Three runs in this series on room air produced a linear correlation coefficient between volume and the reciprocal of helium concentration of not less than 0.999 in each case. Figure 13 shows the third run in the series.

The helium meter was set to read zero for room air before each study. Since nitrogen and oxygen do not have identical thermal conductivities, a change in the concentration of these gases during an FRC measurement could result in an error in the reading of the helium concentration. Errors due to water vapor and carbon dioxide conductivities were cancelled by the appropriate systems. Oxygen-nitrogen correction factors of Suter et al. (1974), derived from testing the catharometer with known gas mixtures and checking the results with gas chromatography were used as follows:

$$He_c = He_d + 9.1 - 46.0 \times F_{O_2} + 13.4 \times (F_{O_2})^2$$

where He_c = corrected helium reading

He_d = direct helium reading

F_{O_2} = oxygen fraction of the gas mixture

These correction factors had been derived on the same catharometer used for this study, as similar instruments deliver

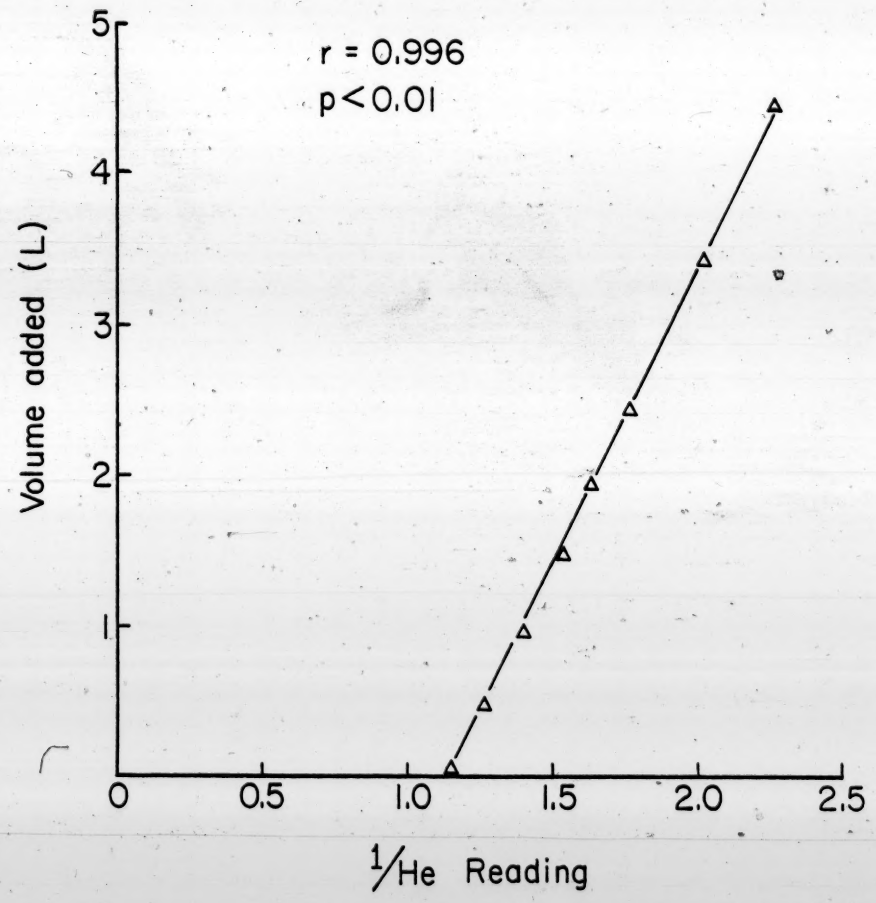

Figure 13. Linearity of the catharometer/spirometer system, assessed by plotting the reciprocal of the helium concentration against the volume of air added to the spirometer.

different correction factors (Suter et al., 1974).

Oxygen analysis. The Beckman E-2 Oxygen Analyzer was used for the oxygen analysis necessary to determine the oxygen-nitrogen correction factors for the catharometer. This instrument contains a measuring cell in which a horizontal glass dumb-bell is suspended in the measuring cell between the poles of the powerful permanent magnets. The dumb-bell contains a diamagnetic gas and is suspended by a platinum filament. It is free to rotate about the vertical axis, and a mirror attached to the dumb-bell gives an optical indication of the degree of rotation. The change of the oxygen concentration in the sample cell alters the relative density of the gas surrounding the ends of the dumb-bell, which causes the dumb-bell to rotate to a new position of equilibrium. The deflected light beam may then be returned to the null position by opposing the torque with a current passed through a coil attached to the dumb-bell. The magnitude of this current is controlled by a potentiometer, and the oxygen concentration is read directly from the potentiometer dial. The zero point is obtained mechanically when the cell contains nitrogen or another oxygen-free gas. The sensitivity is adjusted with dry air or other gas mixtures of known oxygen concentrations (Nunn, Bergman, Coleman, & Casselle, 1964).

It was difficult to determine the accuracy of the Beckman E-2 Analyzer, since its accuracy is generally considered superior to the other reference methods (Nunn et al., 1964). The zero adjustment was made with one hundred per cent nitrogen, the percentage of which had been verified by the method of Scholander. The span was then set with dry medical oxygen, assuming a concentration of 99.8 per cent (Nunn et al., 1964). Subsequently, dry air was introduced to check linearity, which was easily reproducable at a reading of 20.95 per cent. Because of its stability and because of the reproducability of readings, the analyzer was calibrated on only 100 per cent nitrogen and room air prior to each use.

The Beckman E-2 Analyzer indicates the concentration of oxygen in the total gas phase and not only in the dry gas phase. The addition of water vapour to the dry gas, therefore, reduces the indicated value for the oxygen concentration, as well as the presence of other gases. Thus, the sample was withdrawn from the FRC circuit through a leakproof stopcock into a leakproof 100ml glass syringe from the portion of the FRC circuit immediately posterior to the CO_2 absorbent. It was then passed through H_2O absorbent before entering the Beckman E-2 Analyzer. Calibration of the analyzer on nitrogen effectively eliminated the effect of nitrogen on the oxygen reading. In addition, the 100 ml sample was more than sufficient to wash out the cell prior to analysis.

Spirometer. A Warren Collins 6 liter spirometer was included in the circuit. Since the linearity of the system as a whole can be impaired by irregularities in the cross-sectional area of the spirometer bell (Hewlett et al., 1974), its accuracy was checked with a giant syringe. The spirometer was found to be accurate and linear, i.e., serial insertions of one liter and one half liter boluses of air from the syringe produced consistently exactly one liter and one half liter deflections of the writing arm of the spirometer.

System Leaks. As there were a number of connections between the component parts of the FRC circuit, most of which had to be removable for sterilization, the system was conducive to leaks. Two tests were used to check for leaks. First a static, low-pressure test of the entire system was made by placing a one kilogram weight on the spirometer bell. Second, a dynamic, high-pressure test of the inspiratory portion of the circuit was made during the mixing period when the "bag-in-box" was compressed a number of times, producing pressures up to 80 cm of H_2O. During mixing, the one-way valve near the patient's airway was bypassed via a small diameter, high resistance tubing. A change in the baseline of the spirometer tracing representing more than 3 ml per minute indicated an unacceptable leak (Suter et al., 1974).

Whole system. In the assessment of the error of the

method, it was not desirable to use subjects because of the great variability of the FRC with time, gastric filling, and variations in posture. A model system was developed, therefore, in which the known volume of gas in a giant syringe was measured with the FRC circuit but without the use of a ventilator. The plunger of the syringe was manually compressed and then withdrawn by the compression of the "bag-in-box" with an anesthesia bag attached in place of a ventilator.

Measurements of the volume in the giant syringe were made by helium dilution. Six series were performed over a period of several days, three on room air and three on varying concentrations of oxygen. No significant systemic error was found in any of these observations (Table 13). The actual volume measured was 1600 ml, 1500 ml in the giant syringe and 100 ml in the connecting tubing. Because the volume of the connecting tubing was measured by water displacement, it is possible that the actual volume could be in error by a slight amount. The residual apparatus dead space was the same as that used during the actual patient measurements, 4.2 liters.

Duplicate determinations were done under identical ventilatory conditions on ten patients requiring mechanical ventilation for acute respiratory failure. The second value differed from the first by 7 $\pm$ 9 (mean $\pm$ S.D.) per cent, while measured FRC's

Table 13

Measurements of the Volume of the Model

	Series		
	1	2	3
Measurements on Room Air			
Number of measurements	3	4	4
Mean volume (L)	1.606	1.616	1.593
SD (individual measurements)	0.078	0.038	0.014
Range (L)	0.014	0.075	0.029
Coefficient of variation	0.005	0.024	0.009
Measurements on Varying O_2 Concentrations			
Number of measurements	6	3	5
Mean volume (L)	1.622	1.670	1.634
SD (individual measurements)	0.059	0.021	0.055
Range (L)	0.132	0.042	0.115
Coefficient of variation	0.036	0.013	0.034

in these patients ranged from 1429 to 2584.

APPENDIX B

MEASUREMENT OF LUNG-THORAX COMPLIANCE

Lung-thorax compliance is the volume change per unit of pressure change across the lung as measured at the end inspiration no-flow period and calculated according to the following formula:

$$V / P = \frac{V_E}{\text{Plat. P-EEP}}$$

where V_E = exhaled tidal volume

Plat. P = plateau airway pressure

EEP = end expiratory pressure

Method

Airway pressures were obtained from the output of a Harvard Apparatus pressure transducer, connected through an FIO_2 adapter to the proximal end of the inflated endotracheal tube and displayed on the Y-axis of a Hewlett-Packard X-Y Recorder. An inflation hold of 1.0 seconds was used on the volume controlled ventilator in order to obtain pressure recordings at the zero flow period of end inspiration. End-inspiratory pressure measurements were taken from the plateau portion of the pressure curve which most closely represents the static compliance, i.e., that

compliance which is less affected by variation in inspiratory flow rate than the dynamic compliance represented by the peak portion of the curve (Swyer, Reiman, & Wright, 1960). This measurement represents to a greater degree the elastic portion versus the nonelastic portion of the inspiratory resistive pressure.

Exhaled tidal volume was obtained from the output of a wedge spirometer, connected to the proximal end of the inflated endotracheal tube through a Sierra Valve, and displayed on the X-axis of the X-Y recorder simultaneously with the pressure recordings. Since the wedge spirometer collected expired gas, it was possible to record volume tracings on the X-axis over a period of five to ten breaths at a time.

An average value, determined from at least ten respiratory cycles, was used to represent each lung-thorax compliance measurement, because compliance is known to vary somewhat breath-to-breath (Ferris & Pollard, 1960).

Validity and Reliability

Pressure measurements. In the respiratory system, two independent driving pressures are produced. The contraction of the respiratory muscles and the elastic recoil of the chest wall determine the pleural pressure which acts on the outer surface of the lung and which is transmitted to the alveolar airsacs and

airways. The elasticity of the lung generates an elastic recoil pressure which is measured in static conditions, i.e., in the absence of airflow. This static pressure depends on lung volume and on the elastic properties of lung tissue (Clement, van de Woestijne, & Pardaens, 1973).

Since it was impractical to use either direct intrapleural pressure measurements or esophageal pressure recordings, tracheal pressures only were used as a measurement of the compliance of the total respiratory system, including the lung and chest wall. End-inspiratory pressure measurements were used instead of peak pressure changes and were, therefore, less affected by variation in inspiratory flow rate. These measurements represent to a greater degree the elastic portion versus the nonelastic portion of the inspiratory resistive pressure.

The Harvard Apparatus pressure transducer was calibrated immediately prior to each use in centimeters of water pressure. The electrical signal was amplified and displayed on an X-Y recorder. First, the recorder was set to read zero when the transducer was not connected to it. Then, the transducer was connected and left open to room air, and the transducer was balanced so that the recorder was again at zero. A pressure exceeding any to be measured, e.g., 60 cm H_2O, was introduced and the recorder set to read that value. Subsequently, lower

pressures were introduced to determine the linearity of the recording. If there was any deviation from linearity, the entire process was repeated until linear recordings were obtained.

Volume measurements. Expired tidal volume was collected in a wedge spirometer, and the signal from the spirometer amplified and displayed on the X-axis of the X-Y recorder. Accuracy of the spirometer was checked immediately prior to each use, according to the method of Levin, Seleny, Joshi, and Streczyn (1972). Serial volumes of 0.5, 1.0, and 1.5 liters were introduced into the spirometer and the output checked for linearity. Immediately prior to each use, calibration signals of one liter and one-half liter were introduced into the recorder in order to recheck the linearity.

X-Y Recorder. Pressure signals from the Harvard Apparatus pressure transducer were displayed on the Y-axis during inspiration, and volume signals were displayed on the X-axis during expiration. Thus, the signals could easily be read separately, because the wedge spirometer collected expired gas over a period of several breaths causing a cumulative effect of signals to the X-axis, similar to the effect of time.

The accuracy of this method of recording compliance was verified through comparison of the X-Y recorder to a Moselay

10 inch strip recorder, where separate pens were used for the pressure and volume recordings over time. Fourteen separate compliance measurements were made on one patient, using the same pressure transducer and wedge spirometer, first on the X-Y recorder and secondly on the strip recorder. Measurements using the X-Y recorder yielded a compliance of 39.8 $\pm$ 0.8 (mean $\pm$ S.E.), while the measurements using the strip recorder yielded a compliance of 41.2 $\pm$ 1.3 (mean $\pm$ S.E.). No significant difference existed between these measurements. During the latter portion of the data collection for the study, the X-Y recorder became non-functional so the strip recorder was substituted although the same recorder was used on any one subject.

APPENDIX C

BLOOD GAS ANALYSIS

Blood gas tensions and pH were determined by standard electrode techniques used in the laboratory adjacent to the Intensive Care Unit.

Arterial Oxygen Tension

Most gases when dissolved in water or dilute electrolyte solutions exhibit a linear relationship between gas tension and the number of molecules in solution when the temperature remains constant. The solution of oxygen in plasma and whole blood exhibits similar properties. The specific value relating the tension of a gas to the number of its molecules of a particular solution is known as the Bunsen solubility coefficient (α), defined as the milliliters of gas going into solution per ml of fluid, at a specific temperature and a partial pressure of gas above the fluid of 760 mm of mercury, the gas volume being corrected to 0° C. and the standard pressure.

The oxygen detecting device consists of a platinum surface, e.g., cross-section of fine platinum wire, to which an appropriate negative voltage is applied, a silver wire acting as the positive

terminal or anode. Electrical contact is made by immersing both terminals in an electrolyte solution. When oxygen molecules diffuse to the polarized platinum surface, electrolysis of the oxygen occurs. The breakdown of oxygen alters the conductivity of the electrolyte solution and the resulting current is recorded.

Immersion of bare platinum wires into the blood is followed by the deposition of protein on the platinum surface, which interferes with the steady diffusion of oxygen to the electrode. Clark and Wolf (1953) demonstrated that isolation of the electrode and electrolyte system from the blood by means of thin, gas permeable plastic membranes permitted repeated determination of the oxygen tension without the attendant difficulties otherwise imposed by the blood proteins.

The Clark electrode consists of a platinum wire, 25μ in diameter, sealed in glass with the tip exposed by polishing. The platinum and surrounding glass are covered with an oxygen-permeable membrane, holding between itself and the glass and the platinum a film of water containing KCl and a phosphate buffer to prevent the small effect of P_{CO_2} on the response. Also under the membrane, making contact with the KCl solution, is a chlorided silver reference electrode. A potential of -0.7v applied to the platinum results in the passage of a

current that is directly proportional to the availability of oxygen molecules at the platinum surface. By keeping the platinum surface so small and the membrane relatively impermeable, the consumption of oxygen by the electrode results in a fall of about 1.5 per cent or less in P_{O_2} at the electrode membrane surface in blood, as compared to gas, even when the liquid is not stirred. This oxygen electrode can, therefore, be calibrated with gas and does not require equilibration of blood samples with gas. The output current is linear ± 1 per cent from zero to 100 per cent O_2.

The polypropylene-covered electrode with a 25 μ platinum cathode, operated at 37 C has the following characteristics for blood: (1) response time constant of 5 seconds with complete response in 30 seconds; (2) linear response within 1 per cent from zero to 100 per cent oxygen; (3) background current with no oxygen less than the equivalent of 0.5 per cent O_2; (4) blood/gas ratio for equal P_{O_2} = 0.985 at high P_{O_2} (over 100), higher with desaturated blood; (5) temperature coefficient of electrode, 3 per cent per degree centigrade; (6) current output 1 to 3 X 10^{-11} amp per mm Hg P_{O_2} or about 1.5 to 5 X 10^{-9} amp with air; (7) drift usually less than 1 per cent between calibration before and after sample, and

less than 5 per cent per hour; and (8) effect of CO_2 not detectable (Severinghaus, 1965).

Calibration. Arterial oxygen tension measurements and mixed venous oxygen tension measurements were made with a Clark electrode and a Beckman meter. Prior to each analysis the electrode was flushed with room air and the meter set to read 156 mm Hg on a scale of 0-160. If the P_{O_2} was less than 60, it was read on a scale of 0-60, and if greater than 60, it was read on a scale of 0-800. One minute equilibration time was allowed before the reading was made.

Carbon Dioxide Tension

The CO_2 electrode consists of a glass pH electrode covered with a Teflon membrane. A thin layer of water containing salt and bicarbonate ion is held between the glass and Teflon by a spacer (cellophane, Josef paper, nylon stocking, or glass wool). CO_2 gas molecules diffuse through the Teflon from the sample and react with the water to form hydrogen ions. A reference electrode in contact with the water film permits measurement of the resulting pH. With a 0.001^{-M} to 0.01^{-M} bicarbonate solution the output of the electrode is determined by the Henderson-Hasselbach equation:

$$pH = C - \log P_{CO_2}$$

where the constant C is in fact $pK' + \log HCO_3^-/S$. The result is that the electrode senses a pH change of .1 pH unit for a tenfold change in P_{CO_2}. The voltage output of the electrode is directly related to pH and therefore is a log function of P_{CO_2}. For measurements in the normal physiological range, an electrolyte containing 0.01 M or 0.005 M $NaHCO_3$ gives a faster, more linear response. The response time is very slow at a very low P_{CO_2}, and fast at a high P_{CO_2}.

Calibration. The electrode is sensitive to the absolute value of the P_{CO_2} and therefore responds identically to samples of blood, gas, or water. This permits the use of compressed gases for calibration. There is no need to equilibrate with blood with known gas tensions. A gas with a P_{CO_2} within the range of the samples can be used for routine calibration, since response time increases with the difference between the calibrating gas and the sample, and because the transfer of CO_2 that occurs between the blood and the electrode can alter the P_{CO_2} of the sample. The nearer the P_{CO_2} of the calibrating gas is to that of the sample, the less the sample is necessary to flush through the electrode.

Carbon dioxide tension measurements and mixed venous carbon dioxide tension measurements were made with the Severinghaus electrode and a Beckman meter. Prior to each analysis the

electrode was flushed with CO_2 gas close to the range of the arterial carbon dioxide tensions. The actual concentration of the CO_2 in the gas varied between the tanks used. The Beckman meter was then set to read the appropriate CO_2 tension. Heparinized blood was flushed into the electrode and two to three minutes of equilibration time allowed before the reading was taken.

pH

pH was measured with a capillary glass pH electrode with a water jacket for temperature control. The criteria required for accurate determinations of pH in blood are: (1) accurate temperature regulation (within 0.1 C) at or near body temperature; (2) small blood volume with strict anaerobic conditions; and (3) an open, freshly formed, liquid junction between the blood and saturated KCl.

Red blood cells create a potential at the boundary between blood and saturated KCl equivalent to 0.01 pH units. Therefore, 0.01 is added to all pH measurements of whole blood.

Calibration. The pH of arterial and mixed venous blood was analysed with a capillary glass pH electrode and a Beckman meter. A buffer solution was flushed through the electrode, and the meter set to read the pH of the buffer. Heparinized

blood was flushed through the electrode, and then the liquid junction of the pH electrode was rinsed with 2-3 drops of KCl. Readings were made after an equilibration time of 30 seconds to one minute.

APPENDIX D

BLOOD GAS CORRECTION FOR BODY TEMPERATURE

All oxygen tensions, carbon dioxide tensions, and pH reported in this study were corrected to each subject's body temperature.

pH

pH was corrected to each subject's body temperature utilizing the coefficient of -0.0147 pH unit/^{o}C derived by Rosenthal (1948) where:

$$pH_{(\text{Pt.'s temp. } ^{o}C)} = pH_{(37^{o}C)} + (0.0147)\,(37 - \text{Pt.'s temp. } ^{o}C)$$

Whole blood pH rises 0.0147 pH units per degree fall of temperature under anaerobic conditions. The variability of this factor is such that accurate values of pH cannot be relied upon to better than $\pm$ 0.03 if measurements are made at room temperature and corrected to body temperature.

P_{CO_2}

The P_{CO_2} in blood is altered in a reasonably predictable manner by anaerobic changes in temperature. Thus, a correction

can be made for the difference in temperature between the body and the measuring instrument. The change of P_{CO_2} which occurs when the temperature of anaerobically stored blood is changed is expressed by the following empirical equations (Bradley, Stupfel, & Severinghaus, 1956):

$$\frac{\text{gas tension at temperature } T_1}{\text{gas tension at temperature } T_2} = 10f(T_1-T_2)$$

The calculated value for f was 0.0185 at pH 7.40 and temperature within the range of 34-40°C. Experimental determination using human blood (Nunn, Bergman, Bunatyan, and Coleman, 1965) gave a mean value of 0.019 over the range of 18-36 °C. Kelman and Nunn (1966) reported using a value of 0.019.

In programming the Hewlett-Packard 9810 computer for the data analysis of this study, the Bradley et al. (1956) equation was converted to:

$$P_{CO_2} \text{ (Pt.'s temp. } ^{o}C) = (P_{CO_2}) \text{ (37}^{o}C) \left(e^{0.04375\ [\text{Pt.'s temp. } ^{o}C - 37]}\right)$$

P_{O_2}

The P_{O_2} in blood is altered in a reasonably predictable manner by anaerobic changes in temperature. A correction can be made for the difference in the temperature between the body and

the measuring instrument. Oxygen tension changes with temperature in a similar manner to P_{CO_2} according to the Bradley et al. (1956) equation:

$$\frac{\text{gas tension at temperature } T_1}{\text{gas tension at temperature } T_2} = 10^{f(T_1-T_2)}$$

The value of f is, however, in this case markedly influenced by the hemoglobin saturation (Nunn et al., 1965). Kelman et al. (1966) approximated Nunn's experimental data by an empirical expression of the formula:

$$f = 0.0052 + 0.0268 \ (1 - e^{-0.3\chi})$$

where χ is the percentage desaturation. Hedley-Whyte and Laver (1964) also determined the change of P_{O_2} with temperature at full saturation. Their results were in close agreement with Nunn et al. (1965) as were those of Severinghaus (1966).

In programming the Hewlett-Packard 9810 computer for data analysis of this study, the empirical equation of Bradley et al. (1965) was converted to:

$$P_{O_2\ (\text{Pt.'s temp.}^{o}C)} = (P_{O_2})_{(37^{o}C)} \left(e^{[\text{Pt.'s temp. } ^{o}C - 37]\ [0.01197 + 0.0617(1-e^{-0.3\chi})]}\right)$$

where $\chi = 100 - \%S_{O_2}$

Oxygen saturations were calculated from measured oxygen tensions through the use of a mathematical model of a standard dissociation curve applicable to a pH of 7.40, and P_{CO_2} of 40 torr, and a temperature of 37 C, and correction factors which were applied to this standard curve to make it applicable to other temperatures and acid-base states.

The mathematical model describing the dissociation curve is similar to that proposed by Adair (1925) and to the modification of the curve by Kelman (1966):

$$\%S_{O_2} = (25)\frac{a_1P + (2)a_2P^2 + (3)a_3P^3 + (4)a_4P^4}{1 + a_1P + a_2P^2 + a_3P^3 + a_4P^4}$$

The values of the coefficients a_1, a_2, ..., a_4 were determined by fitting the equation in the least-squares sense to paired values of oxygen tension and saturation. In the curve-fitting technique the paired values were weighted appropriately until a satisfactory fit was obtained. The coefficients finally used were:

$$a_1 = 2.1886 \times 10^{-2}$$

$$a_2 = 8.9578 \times 10^{-4}$$

$$a_3 = 4.5060 \times 10^{-6}$$

$$a_4 = 2.4603 \times 10^{-6}$$

In the presence of respiratory or metabolic acid-base disturbance and at temperatures other than 37 C, the computer first calculates the P_{O_2} which would be obtained at a pH of 7.40, a P_{CO_2} of 40 torr, and at a temperature of 37 C. It then converts this P_{O_2} into the percentage saturation via the standard dissociation curve. The equation used to calculate this virtual oxygen tension is:

$$P_{O_2}\ \text{vir} + (P_{O_2})_{(37^{\circ}C)} \left(e^{0.921\ [pH_{37}-7.40] + 0.138\ [\log_{10}40 - \log_{10}PCO_{2_{37}}]}\right)$$

The rationale behind the use of this equation is the generally accepted fact that (except possibly for the pH effect at high saturations) all three factors alter the scale of the P_{O_2} axis but do not alter the shape of the dissociation curve (Roughton, 1964). It is thus possible to make the standard dissociation curve applicable to various temperatures and acid-base states by multiplying all the oxygen tensions by a constant factor.

APPENDIX E

CALCULATION OF ALVEOLAR-TO-ARTERIAL OXYGEN TENSION DIFFERENCE ($A\text{-}aDO_2$)

The alveolar-to-arterial oxygen tension difference was calculated using the alveolar air equation as follows:

$$A\text{-}aDO_2 = P_{A_{O_2}} - Pa_{O_2}$$

where Pa_{O_2} = arterial O_2 tension in torr at pt.'s temp. in C

$P_{A_{O_2}}$ = alveolar O_2 tension

The precise formula for the alveolar air equation is stated as follows (Comroe et al., 1962, p. 339):

$$P_{A_{O_2}} = P_{I_{O_2}} - P_{A_{CO_2}} \left[F_{I_{O_2}} + \frac{1 - F_{I_{O_2}}}{R} \right]$$

where $P_{I_{O_2}} = (P_{BARO} - P_{A_{H_2O}})\ (F_{I_{O_2}})$

This alveolar air equation states that at sea level the total pressure of gases (O_2, CO_2, N_2, and H_2O) in the alveoli equals 760 torr and that if the partial pressures of any three of these four are known, that of the fourth can be obtained by

subtraction. In the process of determining P_{O_2} by subtracting the P_{H_2O}, P_{CO_2}, and P_{N_2}, there are certain measurements and assumptions. It is generally agreed that the water vapor pressure at 37° C is approximately 47 torr. Values for arterial P_{CO_2} which can be measured with reasonable accuracy ($\pm$ 2-3 torr) are used as representative of mean alveolar P_{CO_2}. This is done because the arterial blood coming from all the alveoli approaches an integrated value of alveolar P_{CO_2} with respect to the different regions of the lung and to different times during the respiratory cycle. In addition, CO_2 diffuses through body membranes so readily that its partial pressure in blood leaving any alveolus will always be equal to its partial pressure in the gas of that alveolus. While it is true that non-uniformity of alveolar ventilation with respect to alveolar capillary blood flow through the lung can produce a difference between the P_{CO_2} of mixed capillary blood and mixed alveolar gas in spite of diffusion equilibrium across any single individual alveolus, this difference is relatively small except in the presence of extreme non-uniformity of alveolar ventilation/alveolar blood flow or large venous-to-arterial shunts.

It is also assumed in the foregoing calculation that P_{N_2} = 563 torr. This would be true if the respiratory quotient were 1.0, i.e., it the amount of CO_2 added to the alveoli were exactly

equal to the amount of O_2 removed from the alveoli each minute. In this case, the inspired N_2 would be neither diluted nor concentrated as it entered the alveoli, and alveolar P_{N_2} would equal moist inspired P_{N_2}. In most cases, more O_2 is removed per minute than CO_2 is added. The usual respiratory exchange ratio $(R) = \frac{200 \text{ ml } CO_2/\text{min}}{250 \text{ ml } CO_2/\text{min}} = 0.8$. This results in the N_2 molecules being slightly more concentrated, since the same number of N_2 molecules is now present in a smaller gas volume. Thus, the "correcting" factor of the alveolar equation at the same $F_{I_{O_2}}$ is dependent on the respiratory quotient.

In programming the Hewlett-Packard 9810 computer for the calculations of the data for this study, the respiratory quotient was assumed to be 0.85. In cases where the respiratory quotient was larger, the $P_{A_{O_2}}$ calculated may be slightly low and in cases where the R was smaller, the calculated $P_{A_{O_2}}$ may be slightly falsely high.

APPENDIX F

PHYSIOLOGIC DEAD SPACE CALCULATION (V_D/V_T)

The physiological dead space is defined as that part of the tidal volume which does not participate in gaseous exchange. It is universally defined by the Bohr mixing equation with substitution of arterial P_{CO_2} for alveolar P_{CO_2} (Nunn, 1969, p. 191):

$$\text{physiological dead space} = V_T \frac{Pa_{CO_2} - \bar{P}_{E_{CO_2}}}{Pa_{CO_2} - P_{I_{CO_2}}}$$

where $P_{A_{CO_2}}$ = alveolar CO_2 tension

Pa_{CO_2} = arterial CO_2 tension

$\bar{P}_{E_{CO_2}}$ = mean exhaled CO_2 tension

$P_{I_{CO_2}}$ = mean inhaled CO_2 tension = 0

APPENDIX G

ESTIMATION OF THE SHUNT FRACTION ($\dot{Q}_{VA}/\dot{Q}_T$)

When a patient has a venous-to-arterial shunt, his arterial blood contains some mixed venous blood that by-passed the lungs and some well oxygenated blood that had passed through the pulmonary capillaries. The equation that expresses this relationship for blood is analogous to Bohr's equation for the calculation of respiratory dead space and is based on the axiomatic relationship that the total amount of oxygen in one minute's flow of arterial blood equals the sum of the amount of oxygen in one minute's flow through the pulmonary capillaries and the amount of oxygen in one minute's flow through the shunt. Amount of oxygen in one minute's flow of blood equals the product of the blood flow rate and the concentration of oxygen in the blood.

When the $F_{I_{O_2}}$ is < 1.0, the $\dot{Q}_{VA}/\dot{Q}_T$ is obtained through the following formula:

$$\dot{Q}_{VA}/\dot{Q}_T = \dot{Q}_S/\dot{Q}_T + \dot{Q}_{0.8>\dot{V}/\dot{Q}>0.0}/\dot{Q}_T$$

where $\dot{Q}_{VA}/\dot{Q}_T$ = physiologic shunt or venous admixture

$\dot{Q}_{0.8>\dot{V}/\dot{Q}>0.0}/\dot{Q}_T$ = shunts due to low $\dot{V}_A/\dot{Q}$ or maldistributed ventilation

$$\dot{Q}_S/\dot{Q}_T = \frac{Cc'O_2 - CaO_2}{Cc'O_2 - C\bar{v}O_2}$$

where CaO_2 = arterial oxygen content

$= (Hgb)(S_{O_2})(\gamma) + (P_{O_2})(\beta)$

where γ = 1.34 cc O_2/gm % Hgb

β = 2.9342×10^{-3} (O_2 solubility in plasma with 15 gm % Hgb/ml of O_2/100 ml solution/torr of O_2 pressure

$C\bar{v}O_2$ = mixed venous oxygen content

$Cc'O_2 = (A\text{-}aDO_2)(\beta) + CaO_2$

= end pulmonary capillary O_2 content

$Sa_{O_2} \geq 0.995$

when $Sa_{O_2} < 0.995$, $Cc'O_2$ is increased as follows:

$$Cc'O_2 = (A\text{-}aDO_2)(\beta) + CaO_2 + \left[(Sc'O_2)(Hgb_a[1\text{-}Sa\bar{c}O_2]) - (Sa\bar{O}_2)(Hgb_a)\right](1.34)$$

Arterial and mixed venous blood can be obtained so that

CaO_2 and $C\bar{v}O_2$ may be measured. End-pulmonary capillary blood cannot be obtained for direct analysis of $Cc'O_2$ but its P_{O_2} and hence its C_{O_2} can be estimated by the above formula (Comroe et al., 1962).

APPENDIX H

THE CALCULATION OF CARBON DIOXIDE PRODUCTION ($\dot{V}_{CO_2}$)

$$\dot{V}_{CO_2} = (\dot{V}_E)\ \frac{(P\bar{E}_{CO_2})}{P_{BARA}}$$

where $\dot{V}_E$ = exhaled minute volume

$P\bar{E}_{CO_2}$ = mean exhaled CO_2 tension

P_{BARA} = barometric pressure

(Comroe et al., 1962)

APPENDIX I

THE CALCULATION OF ALVEOLAR MINUTE VOLUME ($\dot{V}_A$)

$$\dot{V}_A = (\dot{V}_E)\ (1-V_D/V_T)$$

where V_E = exhaled minute volume

V_D/V_T = as derived in Appendix F (Nunn, 1969, p. 191)

APPENDIX J

THE CALCULATION OF CARDIAC OUTPUT ($\dot{Q}_T$)

$$\dot{Q}_T \text{ (L/min)} = \frac{\dot{V}_{CO_2}}{(Ca\text{-}\bar{v}_{O_2})\ (8.5)}$$

where $\dot{V}_{CO_2}$ = CO_2 production (cc/min)

$Ca\text{-}\bar{v}_{O_2}$ = a-vCO_2 difference

8.5 = respiratory quotient x 10

The respiratory quotient was discussed in Appendix E together with the problems inherent in using an assumed R of 8.5 in calculating the alveolar air equation. Similar problems exist also in assuming an R = 8.5 in the calculation of cardiac output in that if the R > 8.5 a falsely high cardiac output will be obtained using a standard R of 8.5 and vice versa.

The Fick principle states that the amount of oxygen picked up from the respired gases equals the amount added to the blood which flows through the lungs. Alternatively, the amount of carbon dioxide exhaled equals the amount lost by the blood which flows through the lungs. In the case of oxygen it is evident that the oxygen uptake of the subject must equal the product of

pulmonary blood flow and arteriovenous oxygen content difference (Nunn, 1969, p. 228).

APPENDIX K

UNIVERSITY OF CALIFORNIA AND SAN FRANCISCO GENERAL HOSPITAL

Committee on Human Experimentation Approval #934601

Subject's Name _____ Date _____

I am aware of the investigative procedures to be carried out on the above patient and do not feel that they will jeopardize his condition.

_____

Signature of physician in charge of patient's care

APPENDIX L

UNIVERSITY OF CALIFORNIA AND SAN FRANCISCO GENERAL HOSPITAL

CONSENT TO ACT AS SUBJECT FOR RESEARCH AND INVESTIGATIONS

Committee on Human Experimentation Approval #934601

1) I hereby authorize Mara M. Baun, R.N., and any such assistants as may be selected by her to perform the following procedures and investigations on _____

A) an additional test of lung function

B) withdrawal of extra blood samples from the tubings already inserted into the artery and vein

2) These procedures have been explained to me by

_____.

3) I understand that all of these procedures are frequently performed on patients in the hospital. I further understand that the patient will be carefully monitored during suctioning and should any dangerous or potentially dangerous signs occur, the procedure will be stopped immediately and standard corrective measures taken.

4) I have been informed that the benefits of these studies include the gathering of information which may improve the methods

by which patients are suctioned in the future and the gaining of data about this patient's own heart and lungs which will be immediately available to physicians and nurses.

5) I understand that Mara Baun will answer any questions I may have about the study and that the patient's participation in the study may be terminated at any time without in any way prejudicing medical or nursing care.

_____

Signature of next of kin

_____

Relationship to subject

_____

Signature of witness

APPENDIX M

DATA SHEET

SUBJECT # _____

DATE _____

NAME _____ SEX ____ DATE OF BIRTH _____

HOSPITAL NUMBER _____ HT. ____ WT. ____ AGE _____

DIAGNOSIS _____

_____

_____

T _____ P _____ BP _____ P_B _____

LEVEL OF CONSCIOUSNESS _____

VENTILATOR

TYPE _____ CONTROL or PATIENT TRIGGER

FIO_2 _____ V_T _____ EEP _____

RATE _____

HYPERINFLATION

FIO_2 _____ V_T _____

SUCTION

TYPE OF CATHETER _____ SIZE _____

TYPE OF ET TUBE _____ SIZE _____

SUCTION FLOW _____ L/MIN

AMOUNT OF MUCUS BEFORE SUCTION _____

AMOUNT OF MUCUS SUCTIONED _____

BUCKING _____

ADDITIONAL COMMENTS:

APPENDIX N

PREDICTED FUNCTIONAL RESIDUAL CAPACITY

MEN FRC = (11 X age) + (198 X height) - (20 X weight) - 7220

WOMEN FRC = (-44 X weight) + (550 X SA) - 580

where SA = body surface area in square meters

age = years

height = inches

weight = pounds

(Needham et al., 1954; in Comroe et al., 1962, p. 325)